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ELECTROCHEMICAL MACHINING OF AUTOMATIC GUN BARRELS

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AERONUTRONIC DIVISION
PHILCO-FORD CORPORATION

TECHNICAL REPORT AFATL-TR-74-87

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EGLIN AIR FORCE BASE, FLORIDA

Electrochemical Machining
Of
Automatic Gun Barrels

Richard A. Harlow
Richard C. Kimball

FORWARD

This report was prepared by Philco-Ford Corporation, Aeronutronic Division, Newport Beach, California under Contract Nos. F08635-73-C-0091 and F08635-73-C-0057 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida. The report covers work performed from February 1973 to June 1974. Mr. David Uhrig and Capt Larry R. Lawrence (DLDG) were program managers for each contract, respectively, for the Armament Laboratory.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

A. D. Brown Jr

ALFRED D. BROWN, JR., Colonel, USAF
Chief, Guns, Rockets & Explosives Division

ABSTRACT

A 17-month program was conducted to develop an electrochemical machining process for rifling 25mm, 7-foot-long gun barrels with gain twist rifling. Using a stationary electrode approach, a process and appropriate tooling and operating parameters were developed and demonstrated by rifling two barrels each of 4340 steel, Pyromet X-15 and CG-27, and one barrel each of Pyromet 860 and Alloy 718. Dimensional and metallographic evaluations of the rifled barels verified that this process has high potential as a production rifling technique for steel and superalloy barrels. A producibility study was conducted to predict production costs. A secondary objective of the program was to investigate the feasibility of electrochemically drilling gun barrels in the 25mm size range utilizing a conventional forward flow and a new reverse flow process. The conventional forward flow process showed that deep holes could be drilled, but dimensional control could not be maintained. The reverse flow process showed considerably more promise with improved dimensional control.

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TABLE OF CONTENTS

Title

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (Concluded)

SECTION I

INTRODUCTION

Increasing requirements for improved gun barrel materials have become apparent with the development of new high performance weapon systems. With these new systems, gun barrels must withstand higher muzzle velocities, higher firing rates, and more severe firing schedules, which not only increase barrel erosion rates, but also cause potential barrel overheating and possible structural failure. The Air Force has actively pursued solutions to the high performance barrel problem for several years by funding several research and development programs with the objective of developing new barrel concepts, materials, and fabrication procedures. These programs, as well as internally funded barrel technology programs conducted at the contractor facility, have involved high strength steels and stainless steels, superalloys, and refractory metals. The work has indicated that generally the more erosion-resistant materials are also the most difficult to fabricate by conventional techniques, and before improved materials can be incorporated into new barrel designs, non-conventional high production rate fabrication processes must be developed in order to maintain cost effectiveness.

A significant advancement in barrel fabrication technology was achieved under Air Force Contract F08635-71-C-0209, "Development of an Electrochemical Machining Technique for Rifling Lined Gun Barrels." This contract resulted in development of an electrochemical rifling process for caliber .220 Swift barrels fabricated from gun steel, and iron-base, nickel-base, and cobalt-base superalloys. The process not only produced excellent surface finishes and good dimensional control but also proved to be very rapid and potentially inexpensive when compared with conventional rifling methods. Based on the success of this program, an extrapolation of the process to larger calibers and longer barrel lengths was recommended.

As a follow-on to the small caliber electrochemical rifling work, the Air Force awarded Contract F08635-73-C-0091, "Electrochemical Machining of Automatic Gun Barrels," with the objective of developing an electrochemical rifling process for 25mm, 7-foot-long barrels with gain-twist rifling fabricated from high strength stainless steels and superalloys. Preliminary investigations of electrochemical drilling of gun barrels were also included in this contract, and this effort was subsequently increased by an added task under Contract F08635-73-C-0057, "Fabrication of Composite Test Barrels." This final report documents the electrochemical machining process development work performed under both contracts. A summary of the program and resulting conclusions and recommendations are presented in Section II. Sections III and IV present detailed procedures and results of the development effort, and Section V summarizes an electrochemical rifling producibility study conducted during the program.

SECTION II

SUMMARY

2.1 TECHNICAL APPROACH

The primary objective of the program was to develop an electrochemical machining process for rifling medium caliber (20 to 40mm) gun barrels made from high strength, erosion resistant materials. The intent was to develop a process that could ultimately be scaled up for use as a high volume production technique. A secondary objective was to explore the feasibility of electrochemically drilling gun barrels in an effort to ultimately reduce barrel fabrication costs.

The electrochemical rifling effort consisted of initially developing electrode configurations and electrochemical machining parameters on 12-inch long barrel sections of 4340, Pyromet X-15, Pyromet 860, Alloy 718, and CG-27. The electrode designs and machining parameters were then scaled up for full length (7-foot) barrels, and one or two blanks of each of the five materials were successfully rifled. Two Pyromet X-15 electrochemically rifled blanks were finish machined into GAU-7/A barrels in preparation for future erosion testing.

The electrochemical gun barrel drilling effort consisted of an attempt to establish feasibility by drilling short (8-12 inch) lengths of 4340 steel and Pyromet X-15 utilizing two processes, i.e., the conventional forward flow process and a new reverse flow process. The latter process proved to be the more attractive and several holes with excellent surface finishes were electrochemically drilled in each material. Equipment limitations prevented successful demonstration of adequate dimensional control, but feasibility was clearly established.

2.2 CONCLUSIONS AND RECOMMENDATIONS

Based on the effort briefly summarized above and detailed in Sections III and IV, the following conclusions and recommendations were made:

1. Electrochemical rifling of medium caliber (20 to 40mm) barrels is a very attractive process which offers excellent surface finishes, good dimensional control, and low predicted costs in production quantities.

2. The predicted production electrochemical rifling costs are essentially the same for gun steels, high strength stainless steels, and superalloys. These costs would result in a considerable saving compared to conventional techniques, particularly for difficult-to-machine superalloys.

3. Electrochemical machining appears to be very useful for drilling medium caliber (20 to 40mm) gun barrels. However, additional work is required before scaling up to actual gun barrel lengths can be achieved. This process offers significant potential cost savings on difficult-to-drill alloys.

SECTION III

TASK I - ELECTROCHEMICAL RIFLING PROCESS DEVELOPMENT

The approach for this task was to scale up the electrochemical rifling process developed under Contract F08635-71-C-0209 for Caliber .220 Swift barrels to 25mm, 7-foot-long barrels with gain twist rifling. The procedure consisted of developing tools and electrochemical machining parameters on 12-inch-long, 25mm barrel sections, then scaling-up to the full length 7-foot-long barrel blanks. The following paragraphs present details of the technical effort and results.

3.1 BARREL MATERIALS

The materials selected for this program were Pyromet X-15, Pyromet 860, CG-27, and Alloy 718, which are representative of high strength stainless steels and intermediate temperature iron-base and nickel-base superalloys with potential for use as high performance barrel materials. Also, 4340 steel was used as an inexpensive material for tooling checkout and is representative of a typical gun-barrel steel. The materials were purchased in bar stock form, heat treated, and conventionally gun barrel drilled and honed to an I.D. of 0.984 +0.002/-0.000 inch with a surface finish of 32 rms or better, and straightened to a maximum of 0.010 inch TIR. The barrel blanks were approximately 90 inches long in order to allow trim stock for final machining into an 84-inch-long barrel configuration.

3.2 RIFLING CONFIGURATION

A 14-groove gain twist rifling configuration was selected, as shown in Figure 1. The gain twist coordinates are described in Table I. This rifling geometry was selected to be compatible with the GAU-7/A weapon and ammunition.

3.3 ELECTROCHEMICAL RIFLING PROCESS DESCRIPTION

The results of Contract F08635-71-C-0206 indicated the desirability of utilizing a stationary electrode approach for rifling of gun barrels. This process, shown schematically in Figure 2, involves an insulated copper rod which closely fits into the bore of the barrel blank. Grooves corresponding to the desired rifling configuration are machined through the insulation and into the copper electrode (Figure 3). After the electrode is slipped inside the barrel blank, the electrolyte is pumped into one end of the barrel, through the electrode grooves, and out the other end. A dc voltage is introduced between the electrode (cathode) and the barrel blank (anode) during which a very rapid machining action occurs. By proper design of the electrode grooves and selection of operating parameters (voltage, amperage, time, pressure, temperature, and flow rate), the desired rifling groove depth and geometry are obtained.

A sketch of the electrode is shown in Figure 4. For development purposes, only two grooves were utilized which required indexing seven times to

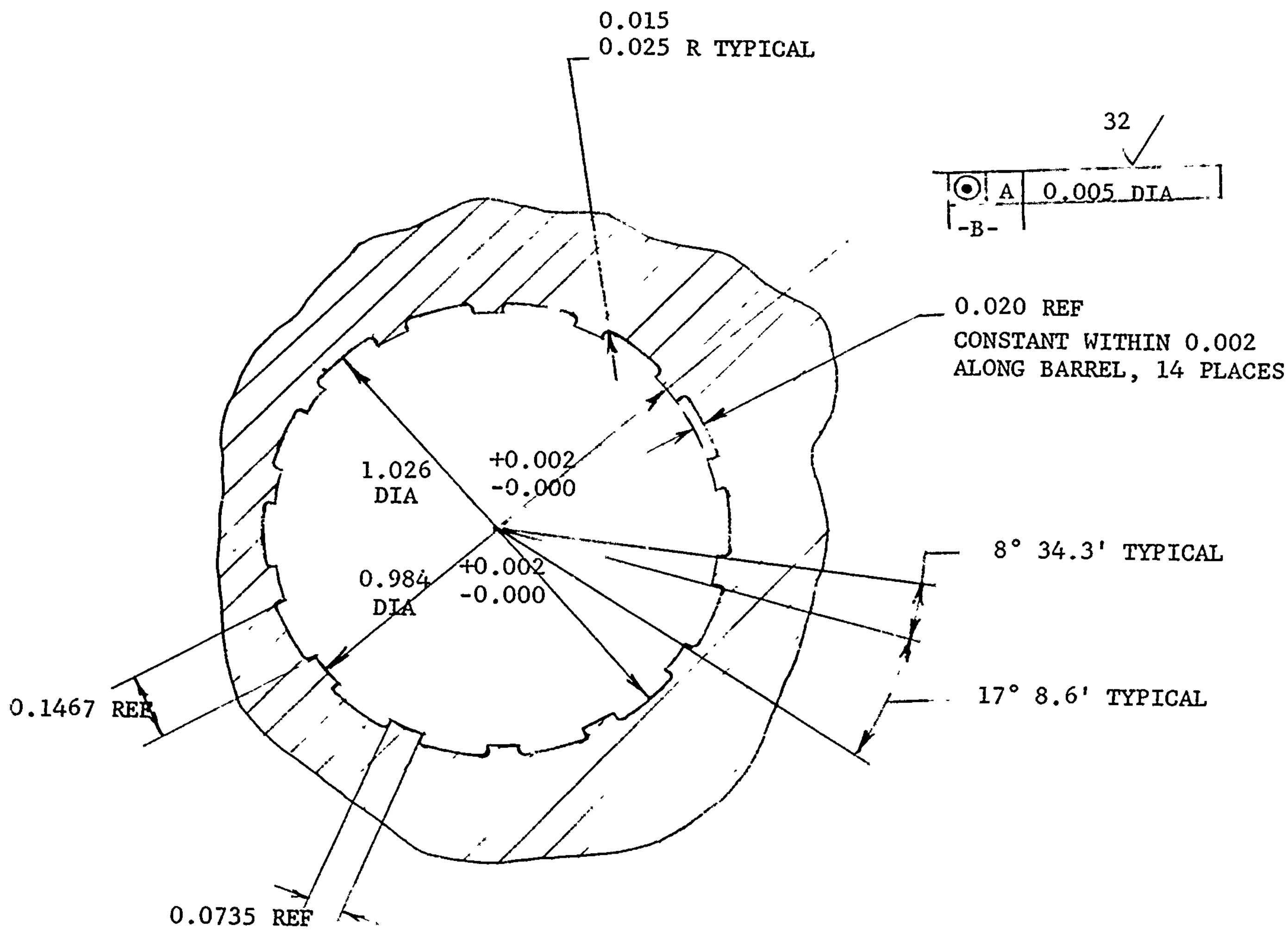


Figure 1. Rifle Groove Geometry for 25mm Gun Barrels

TABLE I. 25mm GAIN TWIST RIFLING COORDINATES

Station (In.)	Rotation Degrees Cumulative	Station (In.)	Rotation Degrees Cumulative
0	0°	42	245° 50'
2	0°	44	266° 37'
2.933	0°	46	288° 8'
3	0°	48	310° 5'
4	0° 42'	50	332° 45'
6	3° 55'	52	356° 2'
8	8° 53'	54	379° 55'
10	15° 16'	56	404° 23'
12	22° 53'	58	429° 27'
14	31° 38'	60	455° 5'
16	41° 27'	62	481° 17'
18	52° 15'	64	508° 3'
20	63° 59'	66	535° 22'
22	76° 37'	68	563° 14'
24	90° 6'	70	591° 38'
26	104° 25'	72	620° 34'
28	119° 31'	74	650° 2'
30	135° 24'	76	680° 1'
32	152° 2'	78	710° 32'
34	169° 24'	80	741° 33'
36	187° 29'	82	773° 5'
38	206° 15'	82.5	780° 47'
40	225° 42'	84	804° 47'

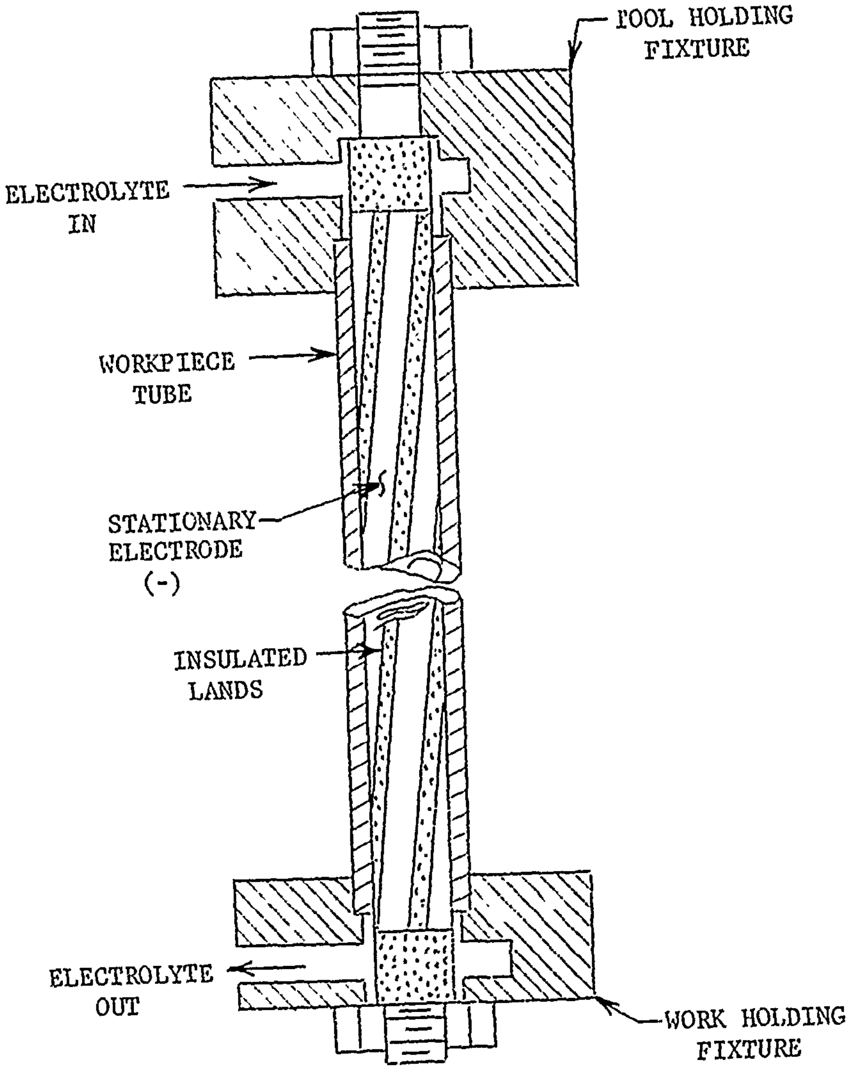


Figure 2. Schematic of Stationary Electrode Electrochemical Rifling Process

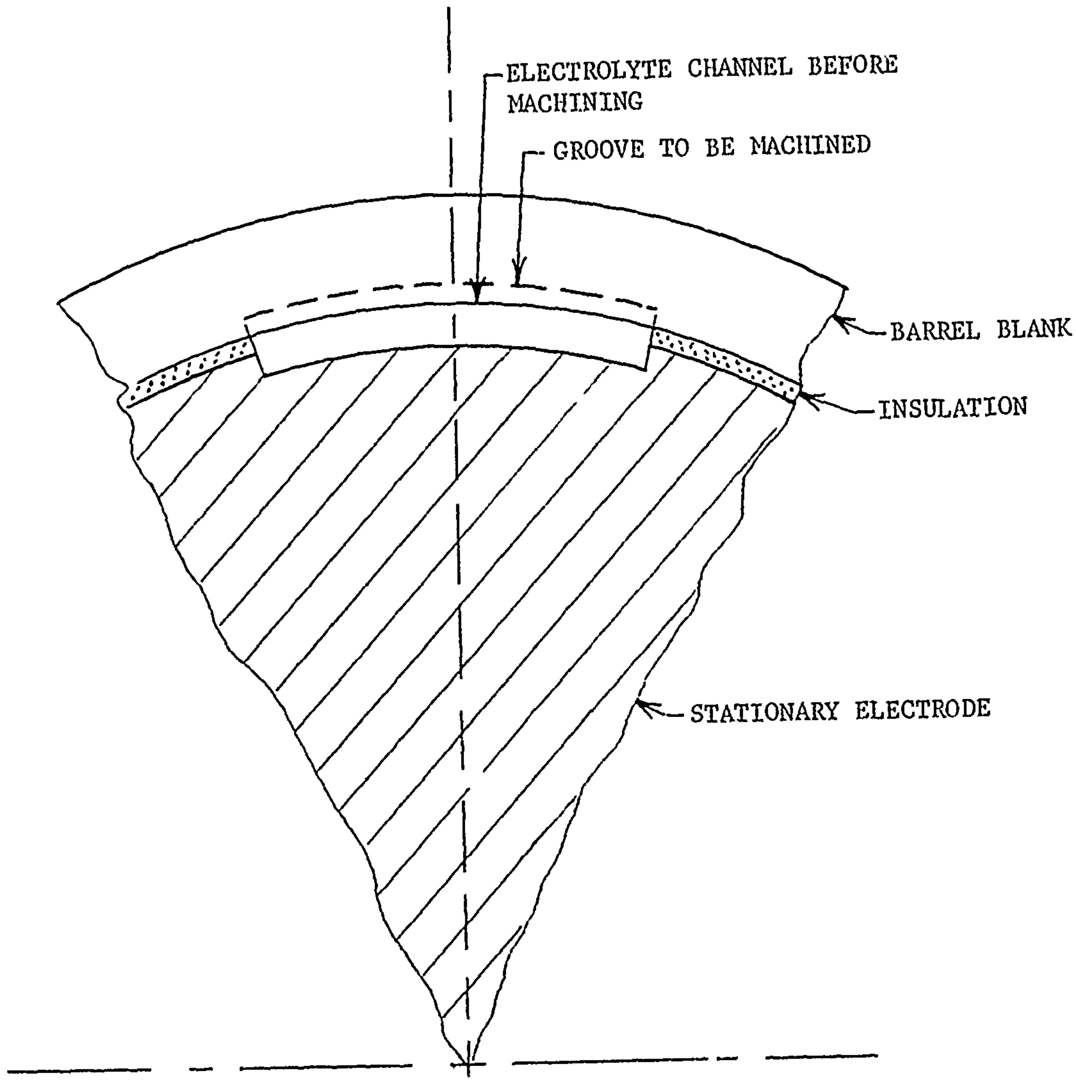


Figure 3. Schematic Cross Section of Groove in Stationary Electrode Inside a Barrel Blank

machine the required number of 14. Obviously in production, the goal would be to machine all 14 grooves simultaneously. The electrode, barrel blank, and associated holding fixtures are shown in Figure 5. The assembled apparatus, ready for machining, is shown in Figure 6.

3.4 DEVELOPMENT OF TOOLING AND ELECTROCHEMICAL RIFLING PARAMETERS

Initial rifling tests were conducted using short length (12-inch) barrel blanks to establish optimum electrolyte and machining parameters for the different materials. Both sodium chloride (NaCl) and sodium nitrate ($NaNO_3$) electrolytes were evaluated with Pyromet 860, Alloy 718, and CG-27 barrels to determine the effect of electrolyte on surface finish and machining rate. Previous work had established that $NaNO_3$ electrolyte would be required to electrochemically rifle the Pyromet X-15 barrels. The short length electrode and tooling set-up are shown in Figure 7.

In addition to the electrolyte studies, tests were run with short length barrels of 4340 steel to determine the effect of electrode groove depth on machining characteristics. During these tests, groove depth was varied from 0.065-inch to 0.125-inch deep (Table II). Satisfactory rifling grooves were obtained with all the different electrode grooves. As a result, an electrode groove depth of 0.125 inch was selected for subsequent tests since the greater groove area allows higher electrolyte flow rates. This results in faster removal of heat and reaction products from the barrel during the machining operation.

Initial tests with the short length 4340 steel barrel blanks were run using 1/2 lb/gallon sodium chloride electrolyte. Two additional tests were run with 4340 using 2 and 2 1/2 lb/gallon sodium nitrate electrolyte (Table II). While surface finishes obtained with sodium nitrate were satisfactory, machining times were longer than those required with the sodium chloride electrolyte.

Tests were run with short length Pyromet X-15 barrel blanks using 1, 1 1/2, 2, and 2 1/2 lb/gallon sodium nitrate electrolyte (Table III). Based on results of these tests, an electrolyte concentration of 2 1/2 lb/gallon sodium nitrate was selected for rifling of full length barrels of Pyromet X-15.

Tests with CG-27 (Table IV) and Pyromet 860 (Table V) showed that sodium chloride electrolyte gave slightly better surface finishes than the sodium nitrate solutions, with essentially equivalent machining rates. Tests with Alloy 718 showed slightly higher machining rates as well as improved surface finishes with sodium nitrate electrolyte compared to the sodium chloride (Table VI).

3.5 ELECTROCHEMICAL RIFLING OF FULL LENGTH BARRELS

The next step in this effort was to extrapolate the parameters and data developed on the 12-inch barrel blanks to electrochemical rifling of full

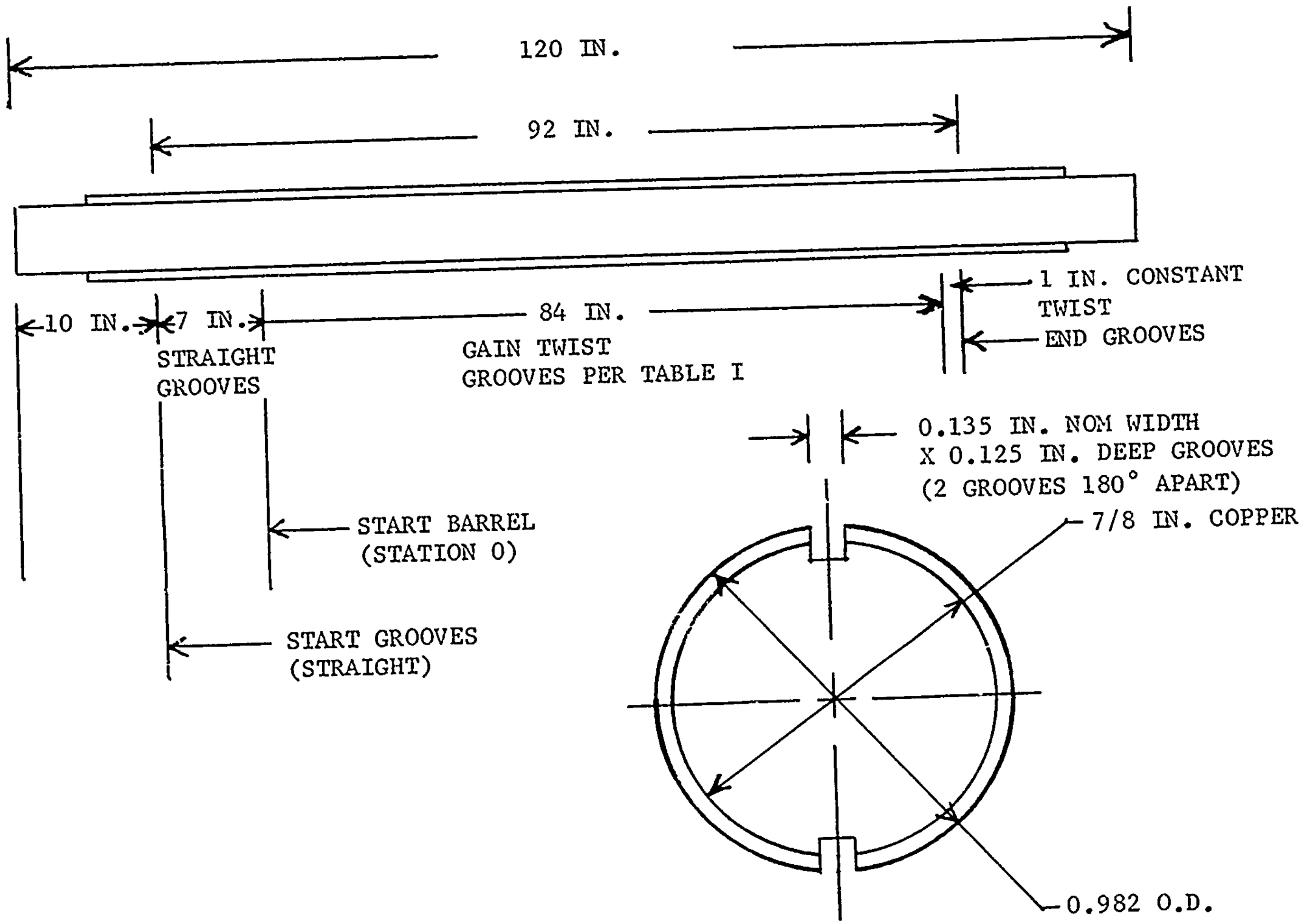


Figure 4. Electrode for Electrochemical Rifling of 25mm Gun Barrels

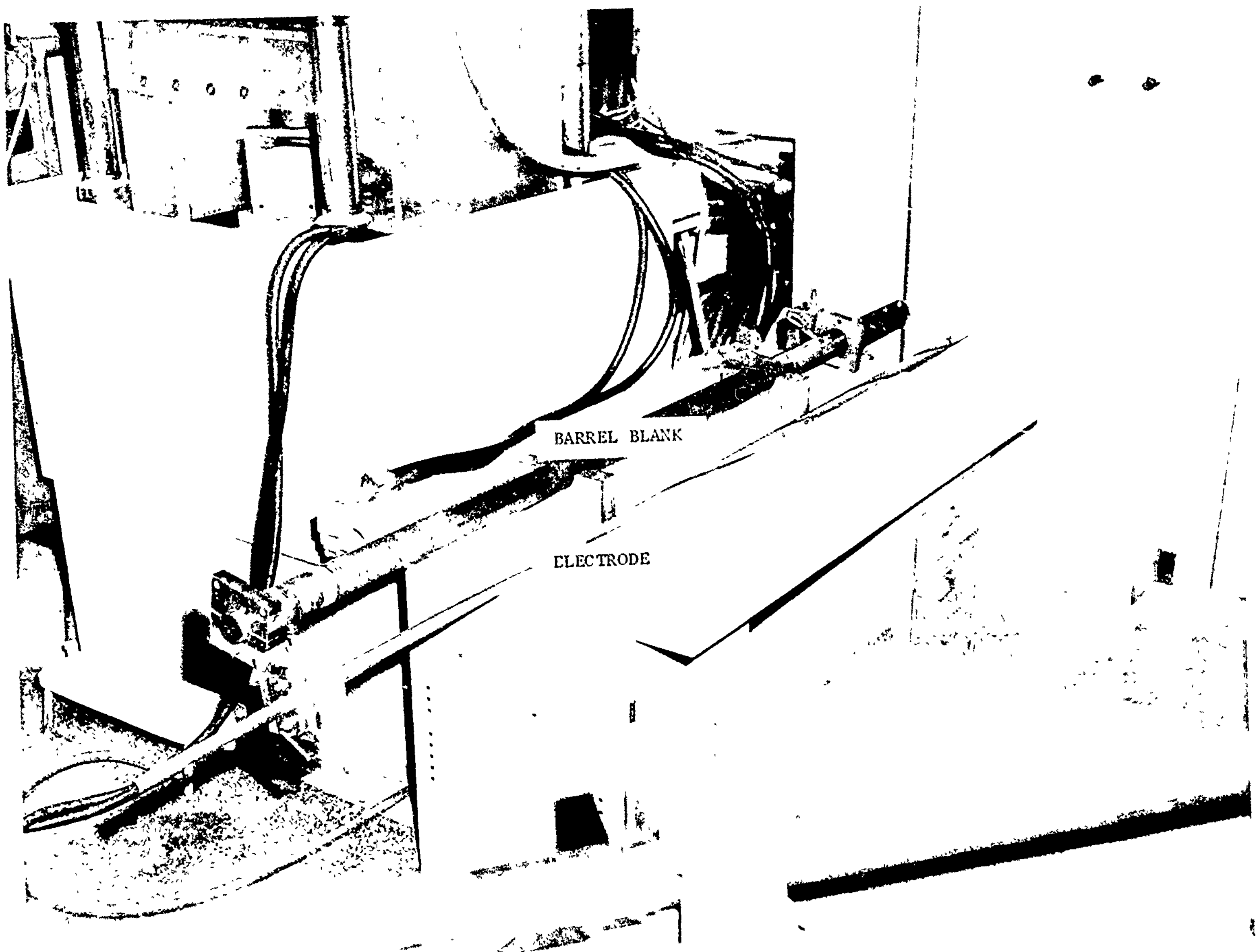


Figure 5. Electrode, Holding Fixtures, and Barrel Blank Ready For Assembly

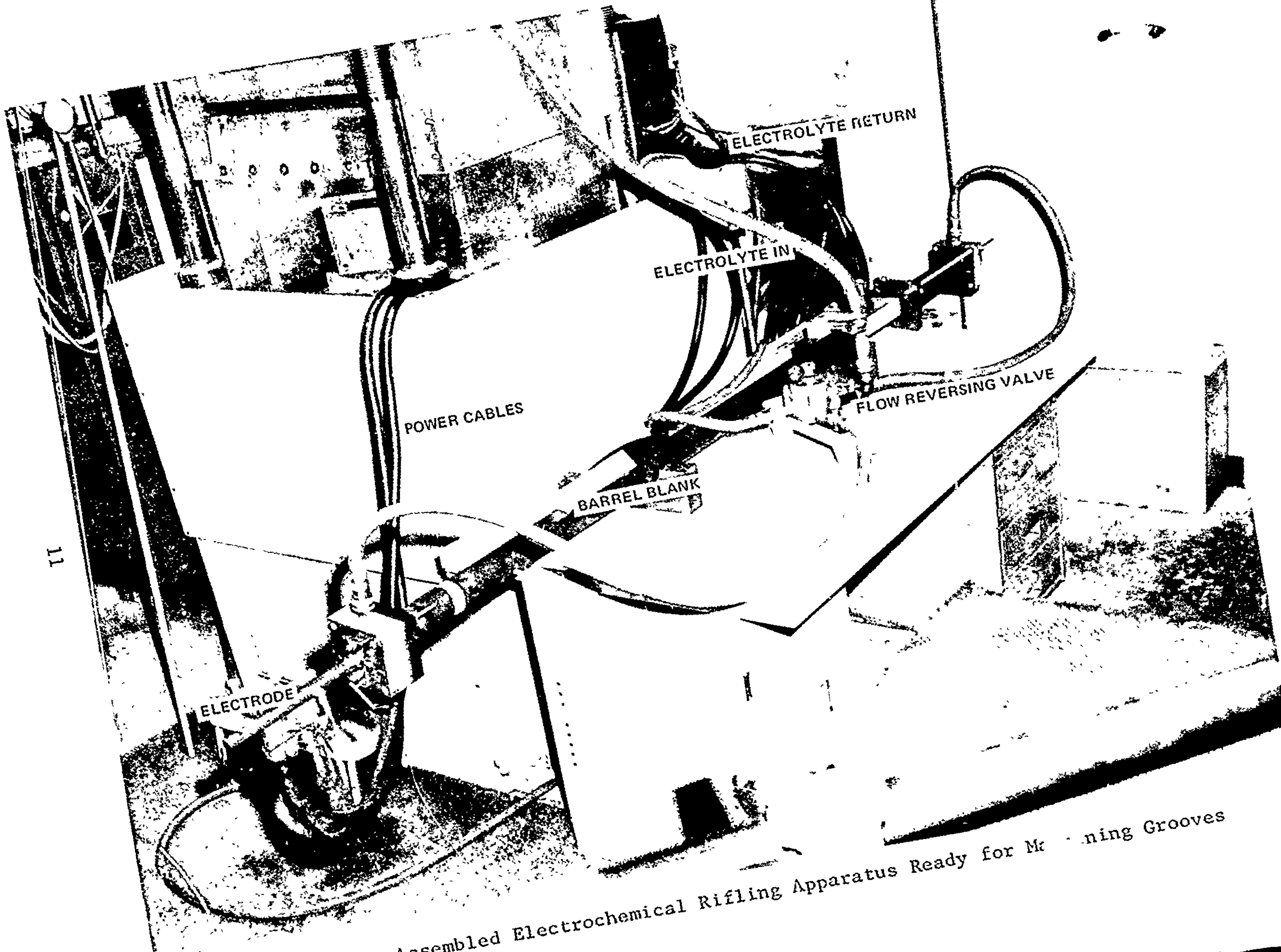


Figure 6. Assembled Electrochemical Rifling Apparatus Ready for M[illegible]ning Grooves

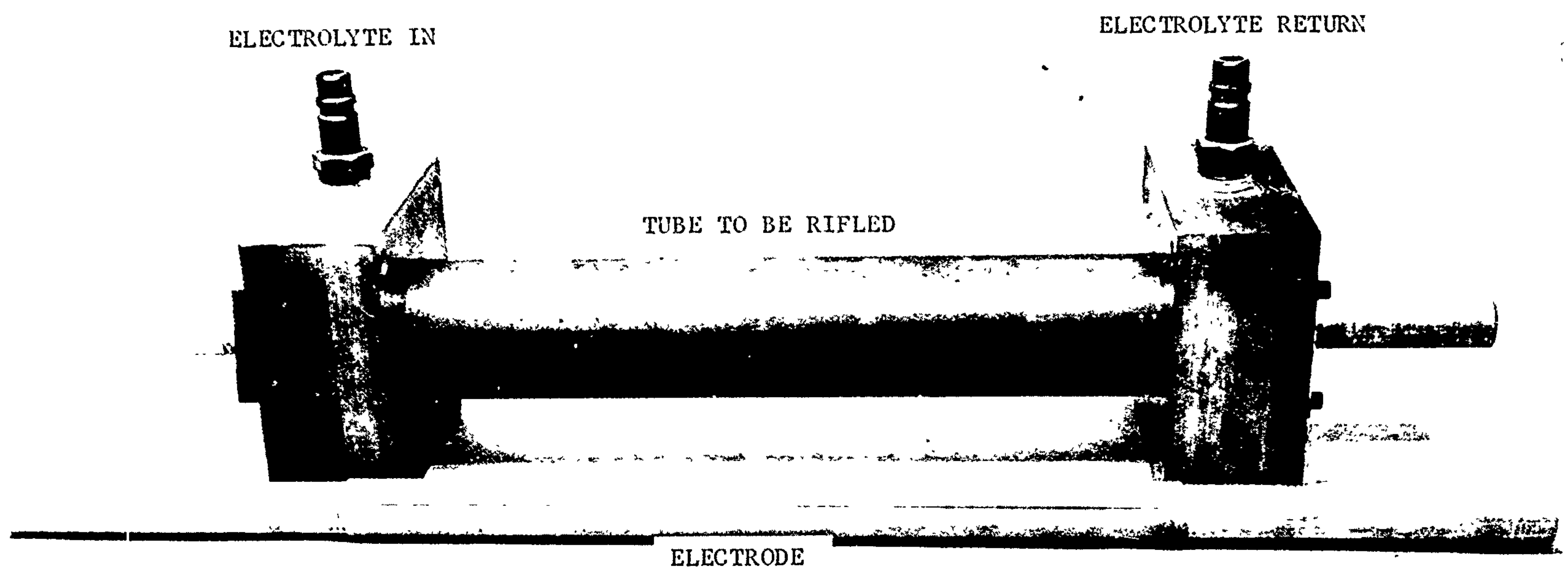


Figure 7. Electrode and Tooling Set-up For Short Length Rifling Tests

TABLE II. ELECTROCHEMICAL RIFLING PARAMETERS - SHORT LENGTH RIFLING TESTS - 4340 STEEL

Test No.	Volts	Amps	Machining Time (Sec)	Pressure (Psi)	Electrolyte Temperature (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Electrode Groove Depth (In.)	Barrel Groove Diameter (In.)
					1/2-LB/GAL NaCl ELECTROLYTE				
1	15	200	240	100	80	2.64	3.84	0.065	1.027
2	15	200	240	100	80	3.20	4.00	0.065	1.0275
3	15	200	240	100	80	4.50	5.28	0.085	1.0215
4	15	200	280	100	80	4.96	5.76	0.085	1.027
5	15	200	280	100	80	5.60	6.32	0.095	1.026
6	15	200	280	100	96	5.44	6.56	0.125	1.0315
7	15	200	250	100	96	6.08	6.88	0.125	1.0265
					2-LB/GAL $NaNO_3$ ELECTROLYTE				
8	17.5	300	600	100	79	5.25	5.89	0.125	1.005
					2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
9	17.5	325	450	100	77	5.28	6.16	0.125	1.026

TABLE III. ELECTROCHEMICAL RIFLING PARAMETERS - SHORT LENGTH RIFLING TESTS - PYROMET X-15

Test No.	Volts	Amps	Machining Time (Sec)	Pressure (Psi)	Electrolyte Temperature (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Electrode Groove Depth (In.)	Barrel Groove Diameter (In.)
					1-LB/GAL $NaNO_3$ ELECTROLYTE				
1	17.5	200	900	100	80	5.44	5.95	0.125	1.002
2	17.5	250	900	100	80	4.08	4.72	0.095	1.010
					1-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
3	17.5	275	600	100	77	4.24	4.96	0.095	1.013
					2-LB/GAL $NaNO_3$ ELECTROLYTE				
4	17.5	500	520	100	77	4.40	5.28	0.095	1.027
5	17.5	300	570	100	77	6.00	6.88	0.125	1.026
					2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
6	17.5	325	360	100	77	5.18	6.08	0.125	1.0235

TABLE IV. ELECTROCHEMICAL RIFLING PARAMETERS - SHORT LENGTH RIFLING TESTS - CG-27

Test No.	Volts	Amps	Machining Time (Sec)	Pressure (Psi)	Electrolyte Temperature (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Electrode Groove Depth (In.)	Barrel Groove Diameter (In.)
					2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
1	15	200	420	100	76	4.48	5.02	0.125	1.040[a]
					1/2-LB/GAL NaCl ELECTROLYTE				
2	17.5	150	300	100	74	6.24	6.80	0.125	1.015[b]

[a]Good appearance - surface slightly rough

[b]Good appearance - surface better than with $NaNO_3$

TABLE V. ELECTROCHEMICAL RIFLING PARAMETERS - SHORT LENGTH RIFLING TESTS - PYROMET 860

Test No.	Volts	Amps	Machining Time (Sec)	Pressure (Psi)	Electrolyte Temperature (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Electrode Groove Depth (In.)	Barrel Groove Diameter (In.)
					2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
1	15	200	540	100	76	4.40	5.20	0.125	1.048[a]
					1/2-LB/GAL NaCl ELECTROLYTE				
2	17.5	175	360	100	75	6.24	6.88	0.125	1.024[b]

[a]Good surface appearance

[b]Better surface appearance than with $NaNO_3$

TABLE VI. ELECTROCHEMICAL RIFLING PARAMETERS - SHORT LENGTH RIFLING TESTS - ALLOY 718

Test No.	Volts	Amps	Machining Time (Sec)	Pressure (Psi)	Electrolyte Temperature (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Electrode Groove Depth (In.)	Barrel Groove Diameter (In.)
					1/2-LB/GAL NaCl ELECTROLYTE				
1	15	200	432	100	95	5.6	6.48	0.125	1.024[a]
					2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
2	17.5	300	300	100	77	5.6	6.56	0.125	1.035[b]

[a]Good surface appearance

[b]Better surface appearance than with NaCl

length, 84-inch-long barrel blanks. The intent was to rifle at least two blanks each of Pyromet X-15 and CG-27, and one each of Pyromet 860 and Alloy 718.

Initially, in order to inexpensively confirm results obtained with short length tests, a full length barrel of 4340 steel was rifled using electrodes having various groove depths (Table VII). The electrodes used in these tests had straight grooves for the entire length of the barrel. Test No. 1 used an electrode having 0.075-inch-deep grooves. Test No. 2 used an electrode having 0.075-inch-deep grooves for 7 inches on each end and 0.085-inch grooves for the middle 76 inches of the groove. Test No. 3, 4, 5, and 6 used an electrode with 0.125-inch-deep grooves to evaluate different operating parameters and electrolytes. Results of these tests (Table VIII) show the following:

1. All tests with sodium chloride electrolyte resulted in deeper machining in the center of the barrel than at the ends of the barrel.

2. Use of an electrode having a step in the center position (Test No. 2) tended to reduce the excess machining in the center of the barrel.

3. Best results were obtained with the electrode having the 0.125-inch-deep grooves.

4. Sodium chloride is the best electrolyte for use with 4340 steel barrels.

Based on tests with the full length, straight groove electrodes, barrels of 4340 steel, Pyromet X-15, Alloy 718, CG-27, and Pyromet 860 were rifled using the gain twist electrode shown in Figures 4 and 5. Electrochemical machining parameters for these operations are shown in Tables IX through XV.

The groove geometries, typified by Figure 8, looked good for all materials. The radius at the base of the grooves was typically 0.060 inch compared to 0.025 inch which was specified for broach rifling. It is believed that such a configuration is entirely satisfactory and may offer advantages of minimizing the shear stresses on plastic rotating bands and of minimizing a potential stress riser (or notch effect) for barrel materials that exhibit marginal fracture toughness. The groove width was intentionally made wider than that specified in order to retain the same available groove volume for the projectile rotating bands.

Surface finish measurements taken at the base of the groove on each material were 32 rms or better for 4340 steel, Pyromet X-15, and Alloy 718 which meets drawing requirements. The CG-27 and Pyromet 860 barrels showed a surface finish of about 150 rms on the grooves. Metallographic examination (Figure 9) was conducted on all materials. No intergranular attack was noted

TABLE VII. PARAMETERS FOR FULL LENGTH RIFLING TESTS OF 4340 STEEL (STRAIGHT GROOVES)

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
							1/2-LB/GAL NaCl ELECTROLYTE			
1	15	1000	2	13	120	100	76	1.28	1.76	2-groove electrode - straight grooves 0.125 in. wide x 0.075 in. deep. Reverse flow every 15 cycles.
2	15	1000	2	13	120	100	78	1.76	2.24	2-groove electrode - straight grooves 0.124 in. wide x 0.075 deep for 7 in. then 0.085 in. deep for 76 in., then 0.075 in. deep final 7 in. Reverse flow every 15 cycles.
3	16	950	2	13	150	100	76	2.80	3.28	2-groove electrode - straight grooves 0.125 in. wide x 0.125 in. deep. Reverse flow every 15 cycles.
4	19	1100	1	9	240	100	80	3.04	3.52	Same electrode as No. 3. Reverse flow every 30 cycles.

TABLE VII. PARAMETERS FOR FULL LENGTH RIFLING TESTS OF 4340 STEEL (STRAIGHT GROOVES) (CONCLUDED)

Test No.	Volts	Amps	Machining Cycle (Sec)		No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm)		Remarks
			Current On	Current Off				Initial	Final	
						1/2-LB/GAL NaCl ELECTROLYTE				
5	16	950	2	18	120	75	78	2.72	3.04	Same electrode as No. 3. Reverse flow after every 15 cycles.
6	17.5	2000	2	13	285	100	75	3.20	3.52	Same electrode as No. 3. Reverse flow after every 15 cycles.

TABLE VIII. GROOVE DIAMETERS OF ELECTROCHEMICALLY RIFLED 4340 BARREL BLANK (INCHES)
(NO-TWIST EXPERIMENTAL ELECTRODE)

Groove[a] Location	Station (Inches From Breech) 1	2	4	6	12	18	24	36	48	60	66	72	78	84	86	88
1	1.018	1.019	1.020	1.021	1.024	1.026	1.027	1.028	1.029	1.028	1.027	1.026	1.024	1.021	1.020	1.019
2	1.021	1.021	1.022	1.023	1.023	1.025	1.026	1.027	1.027	1.027	1.025	1.024	1.023	1.022	1.021	1.020
3	1.028	1.028	1.028	1.029	1.031	1.032	1.033	1.034	1.034	1.033	1.032	1.032	1.030	1.029	1.028	1.027
4	1.027	1.027	1.027	1.028	1.030	1.031	1.032	1.033	1.033	1.032	1.031	1.031	1.029	1.028	1.027	1.027
5	1.019	1.019	1.019	1.020	1.021	1.022	1.023	1.024	1.024	1.023	1.023	1.022	[illegible]21	1.020	1.019	1.019
6	1.021	1.021	1.020	1.019	1.018	1.016	1.016	*	*	*	*	*	*	*	*	*

[a]Refer to Table VII for detailed parameters.

*Undersize. Air gage would not fit into grooves.

TABLE IX. PARAMETERS FOR 4340 STEEL FULL LENGTH BARREL NO. 1

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Machining Cycle (Sec) Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Remarks
							1/2-LB/GAL NaCl ELECTROLYTE			
1	16	1050	2	10	140	100	75	2.80	3.20	89-in-long barrel - Gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - Four inches extra on breech end before 84 in. barrel starts. Reverse flow after every 15 cycles.
2	16	1050	2	10	140	100	76	2.96	3.39	Same as No. 1
3	16	1050	2	10	140	100	81	3.17	3.55	Same as No. 1
4	16	1050	2	10	140	100	83	3.36	3.71	Same as No. 1
5	16	1050	2	10	140	100	78	3.55	3.94	Same as No. 1
6	16	1050	2	10	135	100	80	3.71	4.03	Same as No. 1
7	16	1050	2	10	135	100	83	3.84	4.16	Same as No. 1

TABLE X. PARAMETERS FOR PYROMET X-15 FULL LENGTH BARREL NO. 1

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
							2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE			
1	17.5	1800	2	13	245	100	77	2.56	3.12	89-in.-long barrel - Gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - Four inches extra on breech end before 84 in. barrel starts - Reverse flow after every 15 cycles with flow into breech end and after every 9 cycles with flow into muzzle end.
2	17.5	1900	2	13	240	100	77	2.75	3.26	Same as No. 1
3	17.5	1900	2	13	235	100	77	2.94	3.39	Same as No. 1
4	17.5	2000	2	13	240	100	86	3.17	3.55	Same as No. 1
5	17.5	1900	2	13	235	100	77	3.28	3.71	Same as No. 1
6	17.5	2000	2	13	235	100	85	3.49	3.84	Same as No. 1
7	17.5	2050	2	13	245	100	90	3.65	3.97	Same as No. 1

TABLE XI. PARAMETERS FOR PYROMET X-15 FULL LENGTH BARREL NO. 3[a]

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Machining Cycle (Sec) Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Remarks
						2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
1	17.5	2000	2	10	210	100	66	2.56	3.12	86-3/8-in. long barrel - Gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - 1-1/2 inches extra on breech end before 84 in. barrel starts. Reverse flow after every 15 cycles - Grooves too deep - Electrolyte concentration found to be too high.
2	17.5	2000	2	13	215	100	76	2.80	3.23	Corrected electrolyte concentration. Reverse flow after every 15 cycles.
3	17.5	2100	2	13	215	100	77	2.96	3.36	Same as No. 2
4	17.5	2050	2	13	215	100	77	3.17	3.55	Same as No. 2
5	17.5	2100	2	13	215	100	77	3.33	3.68	Same as No. 2

TABLE XI. PARAMETERS FOR PYROMET X-15 FULL LENGTH BARREL NO. 3[a] (CONCLUDED)

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
						2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE				
6	17.5	2100	2	13	215	100	78	3.44	3.84	Same as No. 2
7	17.5	2100	2	13	215	100	78	3.60	3.92	Same as No. 2

[a]Pyromet X-15 full length barrel No. 2 was slightly oversize dimensionally on the breech end, and was replaced by Pyromet X-15 full length barrel No. 3.

TABLE XII. PARAMETERS FOR INCONEL 718 FULL LENGTH BARREL NO. 1

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Machining Cycle (Sec) Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Flow Rate (Gpm) Final	Remarks
							2-1/2 LB/GAL $NaNO_3$ ELECTROLYTE			
1	17.5	2000	2	13	120	100	76	2.56	3.12	89-in.-long barrel - Gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - Four inches extra on breech end before 84-in. barrel starts. Reverse flow after every 15 cycles.
2	15	1600	2	13	140	100	78	2.75	3.28	Index and run lower voltage to decrease groove depth in center of barrel. Reverse flow after every 15 cycles.
3	13.5	1400	2	13	150	100	80	2.96	3.39	Index and run lower voltage to decrease groove depth in center of barrel. Reverse flow after every 15 cycles.
4	13.5	1400	2	13	154	100	79	3.17	3.55	Same as No. 3.

TABLE XII. PARAMETERS FOR INCONEL 718 FULL LENGTH BARREL NO. 1 (CONCLUDED)

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
							2-1/2-LB/GAL $NaNO_3$ ELECTROLYTE			
5	13.5	1400	2	13	148	100	85	3.36	3.71	Same as No. 3
6	13.5	1400	2	13	148	100	88	3.52	3.87	Same as No. 3
7	13.5	1400	2	13	148	100	89	3.68	4.00	Same as No. 3

TABLE XIII. PARAMETERS FOR CG-27 FULL LENGTH BARREL NO. 1

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
							1/2-LB/GAL NaCl ELECTROLYTE			
1	17.5	1100	2	10	205	100	72	2.72	3.28	89-in.-long barrel - Gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - 4 inches extra in breech end before 84-in. barrel starts. Reverse flow after every 15 cycles.
2	17.5	1100	2	10	205	100	73	2.96	3.42	Same as No. 1
3	17.5	1150	2	10	205	100	77	3.20	3.58	Same as No. 1
4	17.5	1100	2	10	200	100	76	3.28	3.71	Same as No. 1
5	17.5	1150	2	10	195	100	78	3.55	3.81	Same as No. 1
6	17.5	1150	2	10	195	100	79	3.68	3.97	Same as No. 1
7	17.5	1150	2	10	195	100	78	3.84	4.08	Same as No. 1

TABLE XIV. PARAMETERS FOR CG-27 FULL LENGTH BARREL NO. 2

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
							1/2-LB/GAL NaCl ELECTROLYTE			
1	17.5	1050	2	10	205	100	71	2.56	3.12	88-in.-long barrel -gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - 4 inches extra on breech end before 84-in. barrel starts - Reverse flow after every 15 cycles.
2	17.5	1100	2	10	200	100	76	2.75	3.20	Same as No. 1
3	17.5	1100	2	10	200	100	77	2.96	3.30	Same as No. 1
4	17.5	1100	2	10	200	100	77	3.07	3.36	Same as No. 1
5	17.5	1100	2	10	200	100	78	3.20	3.52	Same as No. 1
6	17.5	1100	2	10	200	100	78	3.36	3.65	Same as No. 1
7	17.5	1100	2	10	200	100	78	3.52	3.84	Same as No. 1

TABLE XV. PARAMETERS FOR PYROMET 860 FULL LENGTH BARREL NO. 1

Test No.	Volts	Amps	Machining Cycle (Sec) Current On	Current Off	No. Cycles	Press (Psi)	Temp (°F)	Flow Rate (Gpm) Initial	Final	Remarks
							1/2-LB/GAL NaCl ELECTROLYTE			
1	17.5	1100	2	10	205	100	76	2.72	3.20	89-in.-long barrel - Gain twist electrode - 2 grooves, 0.135 in. wide x 0.125 in. deep - 4 inches extra on breech end before 84-in. barrel starts. Reverse flow after every 15 cycles.
2	17.5	1100	2	10	205	100	74	2.96	3.39	Same as No. 1
3	17.5	1100	2	10	205	100	79	3.17	3.52	Same as No. 1
4	17.5	1100	2	10	205	100	80	3.28	3.68	Same as No. 1
5	17.5	1100	2	10	200	100	81	3.52	3.81	Same as No. 1
6	17.5	1100	2	10	[illegible]	00	82	3.60	3.87	Same as No. 1
7	17.5	1100	2	10	200	100	82	3.76	4.00	Same as No. 1

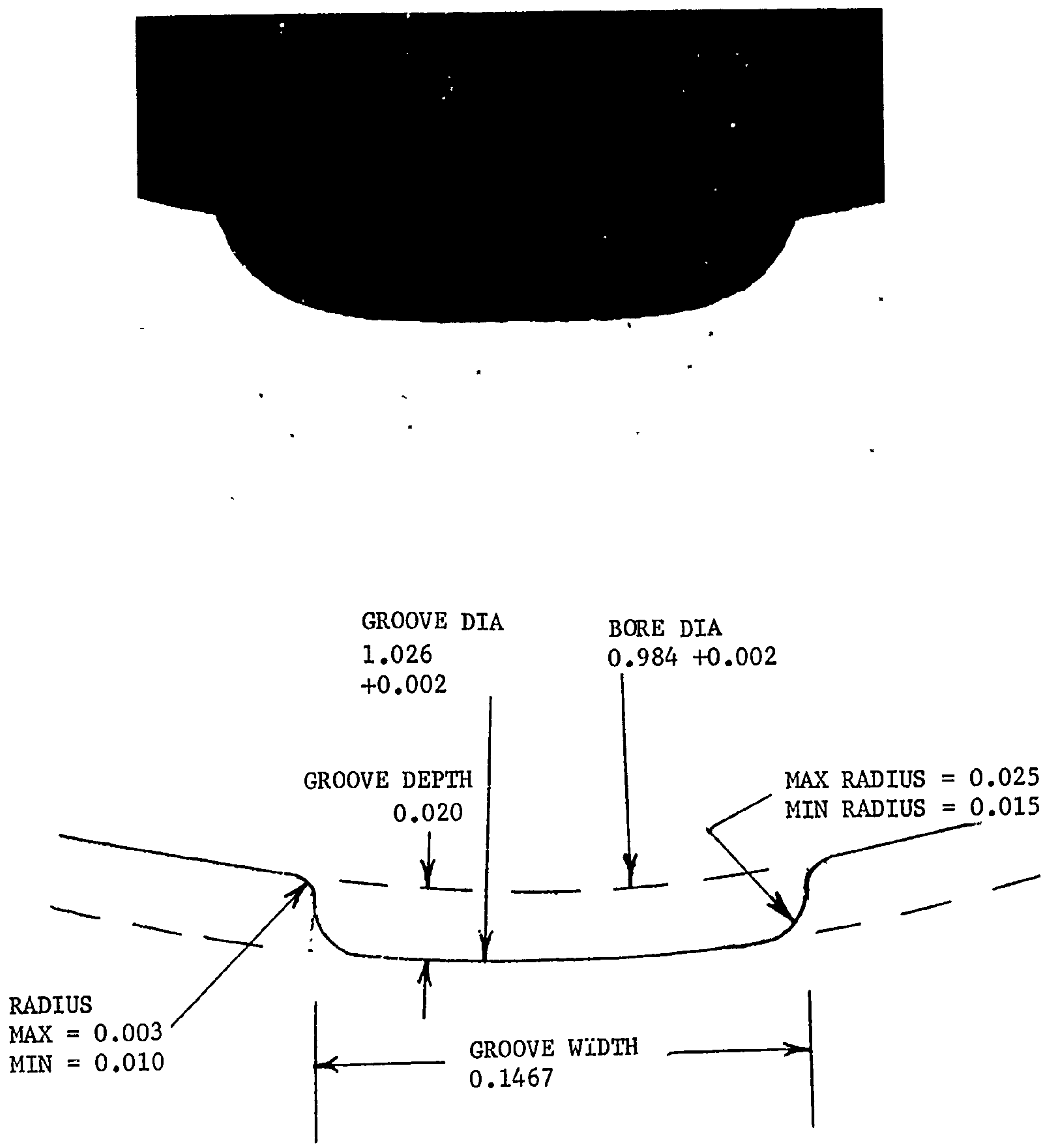
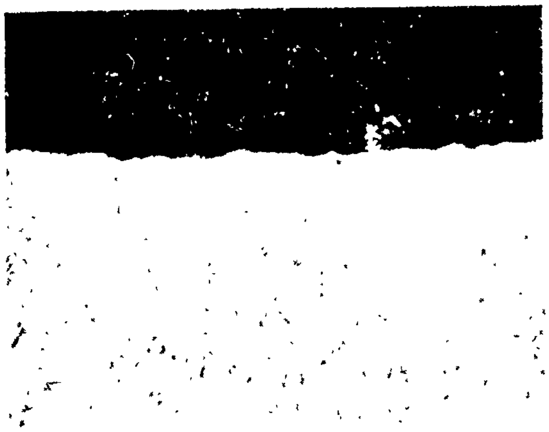
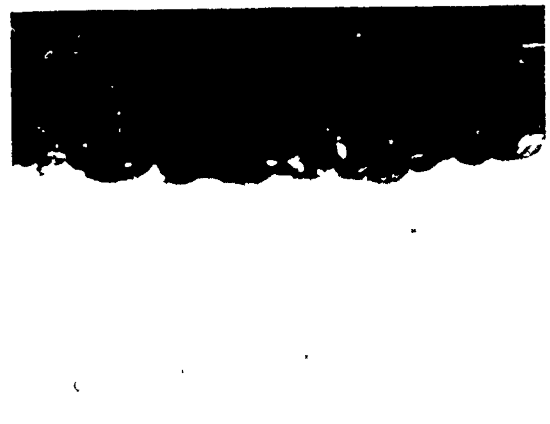


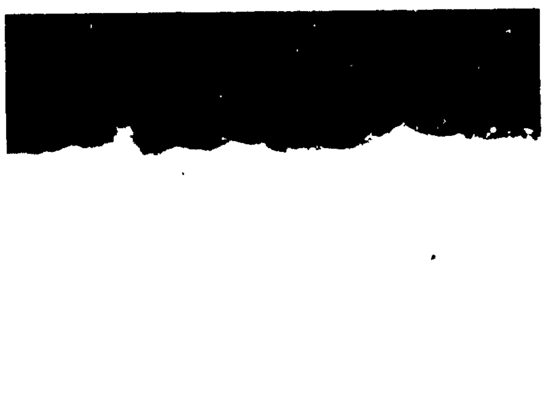
Figure 8. Typical Electrochemically Rifled Grooves, Pyromet X-15



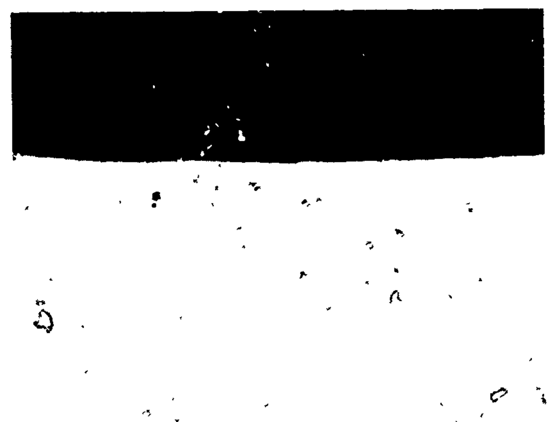
PYROMET X-15 200X



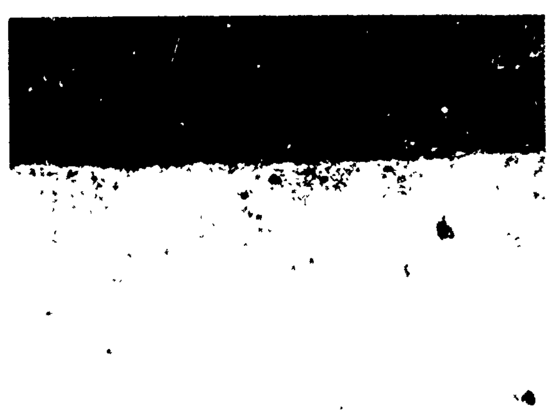
PYROMET 860 200X



CG-27 200X



ALLOY 718 200X



4340 STEEL 200X

Figure 9. Typical Microstructure at Base of Electrochemically Machined Groove Showing No Intergranular Attack

on any of the materials, but the CG-27 and Pyromet 860 showed non-uniform electrochemical machining, probably associated with microsegregation within the alloys, which accounts for their poorer surface finish. Additional optimization of electrolyte composition and electrochemical machine operating parameters would undoubtedly improve this condition and would be desirable prior to a production run.

The electrochemically rifled barrel blanks were air-gauged to determine groove-to-groove and end-to-end variation in groove diameters. The data are summarized in Table XVI. The desired tolerance of 1.026 to 1.028 inches was essentially achieved on the Pyromet X-15, barrel No. 1 except for a few readings that were 1.029. This is considered to be an exceptional achievement with the rather crude equipment and two groove developmental electrode that was utilized. As can be seen from Table XVI, the other barrel blanks were within groove diameter tolerance of $\geq \pm 0.004$, which is still considered highly successful, since only one or two barrels of each material were rifled with the developmental tooling. It is believed that the oversize condition in the mid-position of the barrels resulted from an increase in electrolyte temperature as it was pumped through alternately from each end, thus increasing its machining rate. More work devoted to refinement of the electrode design and operating parameters would undoubtedly be effective in improving the attainable tolerance on a production basis.

3.6 FINISH MACHINING OF PYROMET X-15 TEST BARRELS

The Pyromet X-15 barrel Nos. 1 and 3 were finish machined into a GAU-7/A configuration per Philco-Ford Drawing No. 728495. These barrels, shown in Figure 10, were dimensionally inspected and delivered to the Air Force.

TABLE XVI. GROOVE DIAMETERS OF ELECTROCHEMICALLY RIFLED BARREL BLANKS (INCHES)

Barrel Identity	Groove Location	Station (Inches from breech)						
		2	8	20	44	68	80	84
Pyromet X-15 #1	1	1.027	1.028	1.029	1.028	1.029	1.026	1.026
	2	1.027	1.028	1.029	1.027	1.029	1.028	1.027
	3	1.028	1.028	1.029	1.027	1.027	1.026	1.026
	4	1.027	1.028	1.027	1.027	1.027	1.027	1.027
	5	1.027	1.028	1.028	1.027	1.028	1.027	1.027
	6	1.028	1.028	1.027	1.026	1.027	1.027	1.027
	7	1.028	1.028	1.028	1.027	1.027	1.028	1.028
Pyromet X-15 #3	1	1.028	1.029	1.032	1.036	1.035	1.031	1.027
	2	1.026	1.026	1.027	1.028	1.028	1.028	1.024
	3	1.026	1.026	1.026	1.027	1.028	1.029	1.025
	4	1.026	1.026	1.026	1.027	1.029	1.029	1.025
	5	1.026	1.026	1.027	1.027	1.029	1.029	1.025
	6	1.026	1.026	1.027	1.027	1.029	1.029	1.025
	7	1.026	1.027	1.027	1.027	1.029	1.029	1.025

TABLE XVI. GROOVE DIAMETERS OF ELECTROCHEMICALLY RIFLED BARREL BLANKS (INCHES) (CONTINUED)

Barrel Identity	Groove Location	Station (Inches from breech)						
		2	8	20	44	68	80	84
Pyromet 860 #1	1	1.030	1.030	1.030	1.031	1.029	1.026	1.025
	2	1.030	1.030	1.030	1.031	1.029	1.026	1.025
	3	1.030	1.030	1.030	1.032	1.029	1.026	1.025
	4	1.030	1.030	1.030	1.032	1.029	1.027	1.025
	5	1.030	1.030	1.030	1.031	1.029	1.026	1.026
	6	1.031	1.031	1.030	1.032	1.029	1.027	1.026
	7	1.031	1.031	1.031	1.033	1.030	1.027	1.026
Alloy 718 #1	1	1.027	1.029	1.032	1.034	1.030	1.027	1.025
	2	1.027	1.028	1.030	1.031	1.030	1.027	1.025
	3	1.027	1.028	1.030	1.030	1.029	1.026	1.025
	4	1.027	1.028	1.030	1.030	1.028	1.026	1.025
	5	1.027	1.028	1.029	1.030	1.029	1.026	1.025
	6	1.027	1.028	1.030	1.031	1.029	1.027	1.025
	7	1.027	1.028	1.030	1.031	1.029	1.027	1.025

TABLE XVI. GROOVE DIAMETERS OF ELECTROCHEMICALLY RIFLED BARREL BLANKS (INCHES) (CONTINUED)

Barrel Identity	Groove Location	Station (Inches from breech)						
		2	8	20	44	68	80	84
CG-27 #1	1	1.026	1.028	1.030	1.031	1.030	1.026	1.025
	2	1.027	1.029	1.031	1.032	1.029	1.027	1.026
	3	1.029	1.030	1.032	1.034	1.031	1.029	1.027
	4	1.028	1.029	1.030	1.032	1.029	1.028	1.026
	5	1.027	1.028	1.030	1.031	1.029	1.027	1.026
	6	1.027	1.027	1.029	1.031	1.028	1.027	1.026
	7	1.027	1.027	1.030	1.030	1.029	1.027	1.026
CG-27 #2	1	1.025	1.026	1.029	1.029	1.027	1.024	1.024
	2	1.026	1.027	1.029	1.030	1.028	1.025	1.024
	3	1.026	1.027	1.029	1.030	1.027	1.025	1.024
	4	1.026	1.028	1.030	1.031	1.028	1.025	1.024
	5	1.027	1.028	1.030	1.032	1.029	1.026	1.024
	6	1.027	1.029	1.031	1.032	1.029	1.027	1.025
	7	1.028	1.029	1.031	1.032	1.030	1.026	1.026

TABLE XVI. GROOVE DIAMETERS OF ELECTROCHEMICALLY RIFLED BARREL BLANKS (INCHES) (CONCLUDED)

Barrel Identity	Groove Location	Station (Inches from breech)						
		2	8	20	44	68	80	84
4340 Steel #1	1	1.025	1.026	1.027	1.029	1.027	1.025	1.023
	2	1.026	1.027	1.029	1.030	1.028	1.026	1.024
	3	1.028	1.029	1.030	1.032	1.029	1.027	1.025
	4	1.028	1.029	1.031	1.032	1.029	1.027	1.026
	5	1.027	1.027	1.029	1.030	1.028	1.026	1.025
	6	1.026	1.027	1.029	1.030	1.028	1.025	1.025
	7	1.027	1.028	1.029	1.030	1.027	1.025	1.022

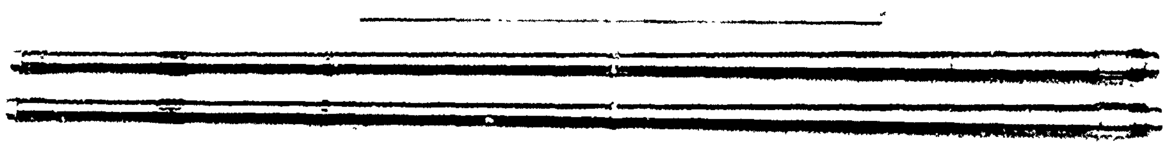


Figure 10. Electrochemically Rifled GAU-7/A Barrels

SECTION IV

TASK II - ELECTROCHEMICAL GUN DRILLING INVESTIGATION

The goal for this task was to investigate the feasibility of electrochemical gun barrel drilling in the 25mm size range. Gun drilling costs represent a significant portion of barrel manufacturing costs, particularly for difficult-to-drill alloys. This effort was directed toward determining if electrochemical gun drilling showed potential for competing with conventional techniques on the basis of quality and ultimate production cost.

4.1 BASIC APPROACHES FOR ELECTROCHEMICAL GUN BARREL DRILLING

Two basic approaches, shown schematically in Figure 11, were investigated. The conventional forward flow process (Section 4.3) which was investigated initially was useful in demonstrating feasibility but indicated that considerably more development effort was required. Subsequently, a new reverse-flow process (Section 4.4) was investigated with much more encouraging results.

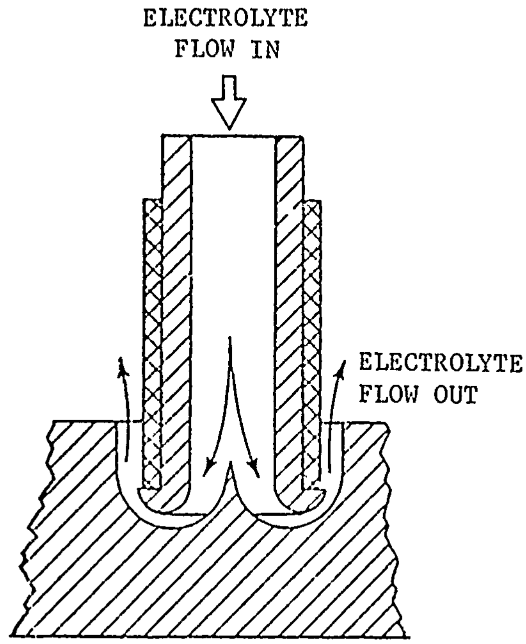
Both processes involve an electrode which is placed in a machine having a movable head, and the part to be drilled was secured directly below the electrode. A typical set up for the conventional forward flow process is shown in Figure 12. During this machining operation the electrolyte is pumped through the center hole of the electrode and out across the tip. Simultaneously a dc potential is imposed, with the electrode being negative and the workpiece positive. The electrode is slowly fed into the workpiece, and the metal directly in front of the electrode tip is dissolved electrochemically. This results in a machined hole which has the same configuration as the electrode tip. The reverse flow process is similar except that the fresh electrolyte is pumped from the outside of the electrode across the cutting tip, and back out through the center of the electrode. Since the charged electrolyte and machining residue does not come in contact with the machined surface, stray and uncontrolled etching is minimized as discussed below. A sketch of the electrode used for both processes is shown in Figure 13. Figure 14 shows the pressure-seal arrangement utilized for the reverse-flow process.

4.2 MATERIALS

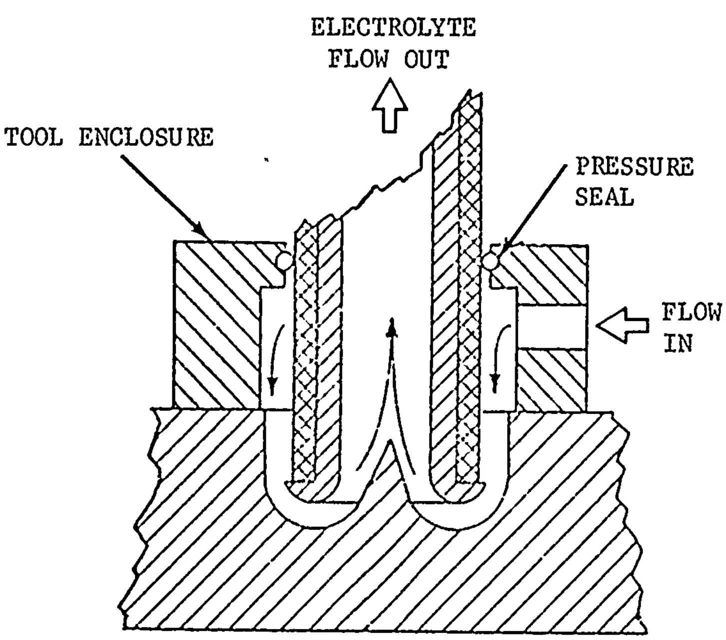
Two materials, 4340 steel and Pyromet X-15, were selected for this task. These were selected as the two least expensive of the potential barrel materials for Task I and were considered to be representative, since all of the materials exhibit very similar electrochemical machining characteristics. The 2-3/4-inch diameter bar stock was heat treated and cut to 8 or 12-inch lengths in preparation for the gun barrel drilling trials.

4.3 ELECTROCHEMICAL DRILLING TRIALS (FORWARD FLOW)

The initial test on this task (Test No. 1, Table XVII), using sodium chloride electrolyte and a 4340 steel bar, resulted in failure of the insulation on the electrode. This failure caused the side of the barrel wall to wash out and become uneven adjacent to the points of insulation failure. The electrode was reinsulated using fiberglass/epoxy insulation, and testing was continued.



FORWARD FLOW



REVERSE FLOW

Figure 11. Forward and Reverse Flow Techniques

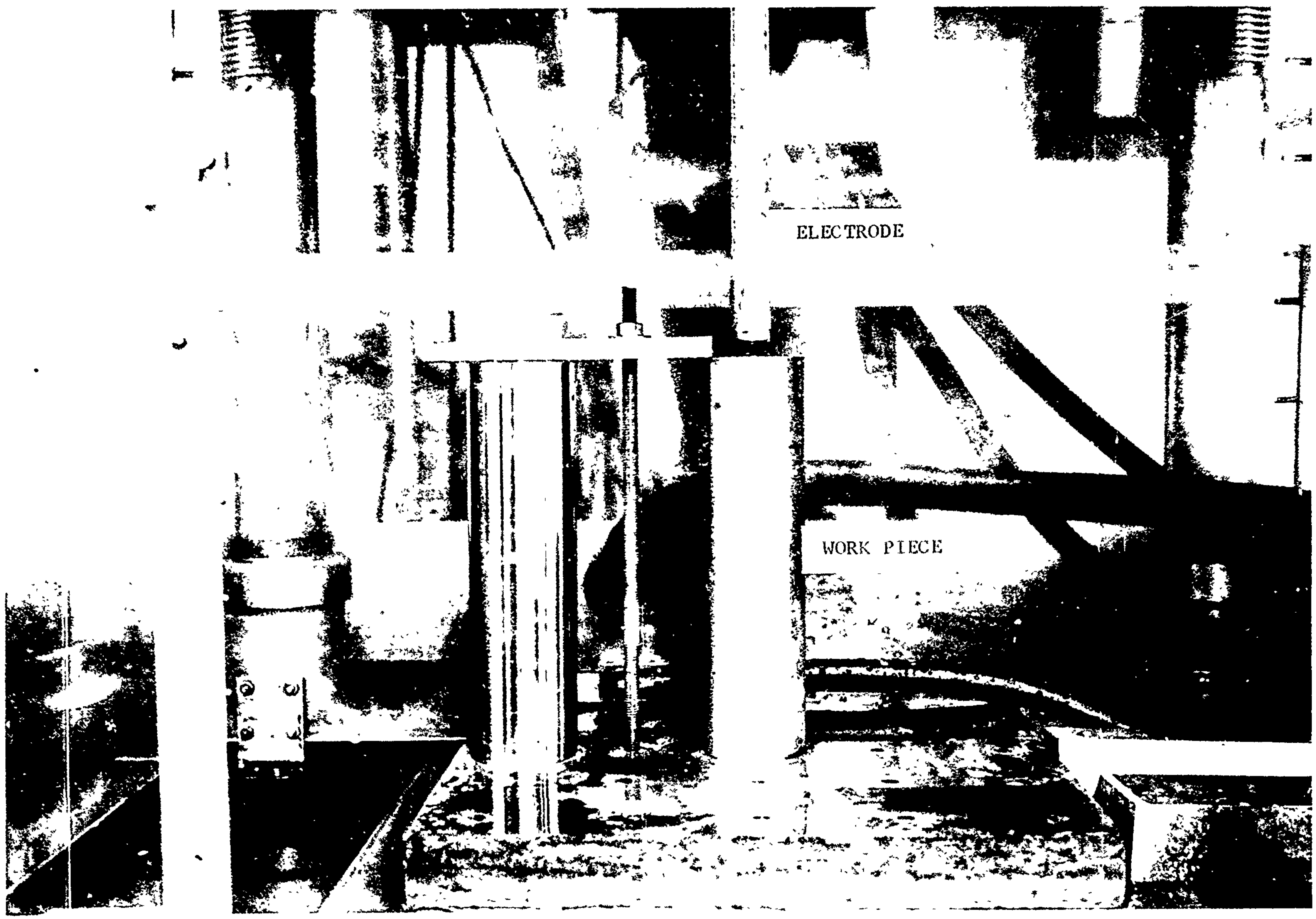


Figure 12 Test Set-up For Electrochemical Gun Barrel Drilling (Forward Flow)

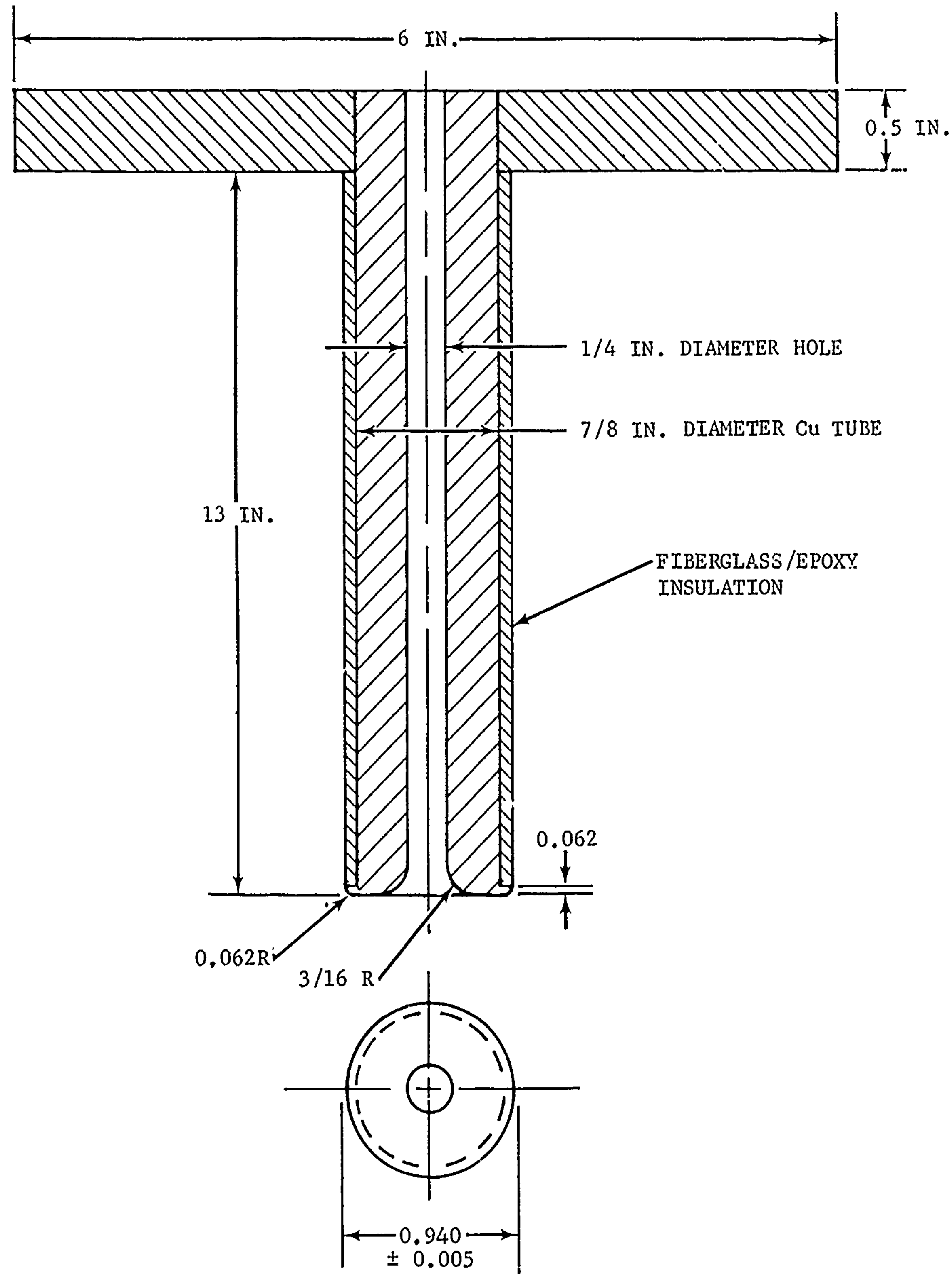


Figure 13. Electrode - 25mm Gun Drilling

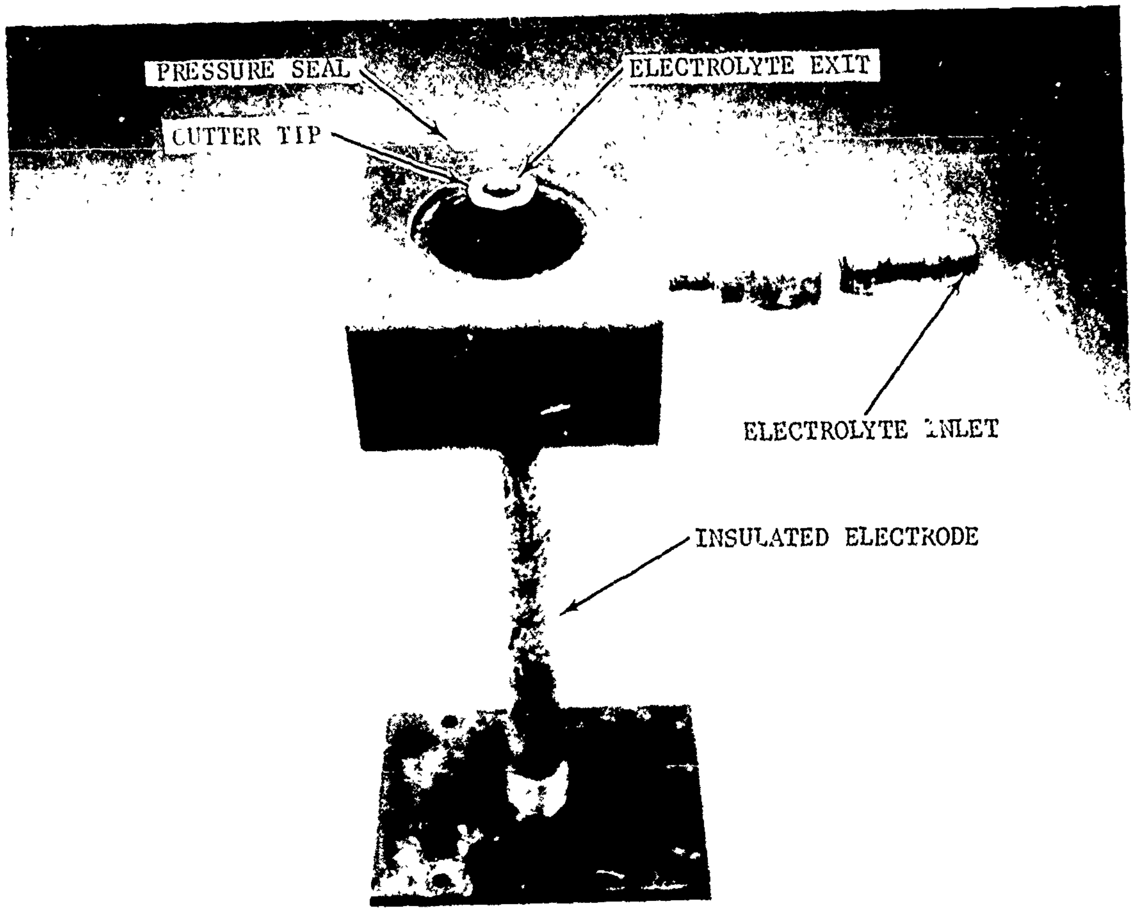


Figure 14. Electrode With Pressure Seal for Reverse Flow Technique

TABLE XVII. ELECTROCHEMICAL MACHINING PARAMETERS - 4340 STEEL
25mm GUN DRILLING TESTS (FORWARD FLOW)

Test No.	Volts	Amps	Feed Rate (In/Min)	Pressure (Psi)	Electrolyte[a] Temperature (°F)	Flow Rate (Gpm)	Remarks
1	20	220	0.047	130	100	8.0	Used 13-in.-long electrode, epoxy insulation, tip diameter 0.950 in.
	20	325	0.070	160	100	6.5	Increased rate to 0.070 inch/minute at 1 in. depth. Shut down at 2.5 in. deep. Insulation blistered on electrode. Hole washed out in spots.
2	15	220	0.050	150	80	5.3	Used 13-in.-long electrode-fiberglass/epoxy tape insulation-tip diameter 0.950 in.
	Sparked out at 0.590 in. - restarted.						
	15	230	0.050	155	85	5.3 (at 2 in.)	Hole looked good. Hole diameter 0.980 in.
	Sparked out at 4.486 in. - restarted.						
	15	235	0.050	160	92	5.6 (at 5 in.)	Electrode tip shorted on edge, apparently due to vibration of electrode.
	Sparked out at 5.080 in. - could not restart.						
3	15	180	0.050	150	76	5.3	Used spacers on side of electrode. Tip diameter 0.950 in. Spacer diameter 0.965 in.
	Sparked out at 0.130 in. - restarted at 17.5 volts.						
	17.5	195	0.050	150	76	6.5 (at 1 in.)	Removed tool at 1.305 in. deep. Tip shorted around edge, apparently due to vibration.
	Sparked out at 1.232 in. - restarted.						
	Sparked out at 1.284 in. - restarted.						
	Sparked out at 1.305 in. - shut down.						
4	17.5	185	0.050	150	77	6.90	Reworked tip and spacers. Tip diameter 0.940 in., spacer diameter 0.965 in.
	Sparked out at 3.140 in. - restarted.						
	17.5	200	0.050	160	92	7.4 (at 5 in.)	Increased rate to 0.060 in./minute at 5 in. deep.

TABLE XVII. ELECTROCHEMICAL MACHINING PARAMETERS - 4340 STEEL 25mm GUN DRILLING TESTS (FORWARD FLOW) (CONCLUDED)

Test No.	Volts	Amps	Feed Rate (In/Min)	Pressure (Psi)	Electrolyte[a] Temperature (°F)	Flow Rate (Gpm)	Remarks
	17.5	240	0.050	160	95	6.2 (at 6 in.)	
	17.5	240	0.050	160	100	6.4 (at 7 in.)	
	17.5	245	0.050	160	103	6.6 (at 9 in.)	Shut down at 9.550 in. deep. Hole rough and uneven. Excessive stray etching at top of hole.

[a] 1/2-lb/gallon NaCl

In Test No. 2, a hole was drilled 5.080 inches deep at which point the tip of the electrode shorted out against the workpiece and shut down the machine. This apparently was caused by the electrode vibrating inside the hole and touching the side of the hole.

For subsequent tests, spacers were placed on the electrode near the tip to minimize the vibration of the electrode. A hole was drilled 9.550 inches deep in a 4340 steel bar (Test 4); however, the hole was rough and uneven due to excessive stray etching on the side of the hole from the sodium chloride electrolyte.

Electrochemical gun barrel drilling trials were run on Pyromet X-15 bar using a sodium nitrate electrolyte (Table XVIII). The walls of the hole were smooth, but the hole was uneven on the inlet and walls. This was apparently due to turbulence of the electrolyte caused by flow around the spacers. The hole appearance was very good below the spacers.

It is believed that the difficulty in controlling dimensions during the electrochemical gun barrel drilling resulted primarily from stray etching along the hole during exit of the electrolyte. The magnitude of this problem was probably related to varying amounts of machining residue which undoubtedly affect the conductivity of the electrolyte.

4.4 ELECTROCHEMICAL DRILLING TRIALS (REVERSE FLOW)

In contrast to the forward-flow trials (Section 4.3) no problems with electrode vibration or shorting were encountered during the trials with the reverse flow tooling. However, although this effort was considered very successful, two major problems impaired achievement of an optimum demonstration of the process, i.e. (1) power supply failures, and (2) inadequate electrolyte cooling capability, both of which were strictly equipment problems. The lack of adequate electrolyte cooling capability presented a problem with the control of hole size during the drilling operation. During machining, heat is generated, resulting in an increase in the temperature of the electrolyte. As the electrolyte temperature increases, the conductivity also increases causing a slight increase in the machining rate. This in turn causes the overcut (gap between the electrode tip and the wall of the hole) to increase. As a result, the holes drilled during this program increased in size from the top to the bottom of the part, due to the increase in electrolyte temperature as the hole was being drilled. With an adequate cooling system this problem would not be encountered.

During electrochemical machining operations, the major factors affecting hole size are (1) machining voltage, (2) electrolyte conductivity, and (3) feed rate of the tool into the part. In general, feed rates are set as high as possible to reduce machining times.

During initial tests to drill 4340 steel (Test No. 1, Table IXX) machining was started at a feed rate of 0.05 in/min at 20 volts. The rate was increased to 0.075 in/min and drilling was proceeding satisfactorily until a power supply failure occured at 2.692-inches deep. On Test No. 2, machining was started at 0.075 in/min and increased to 0.10 in/min where it was maintained for the remainder of the test.

TABLE XVIII. ELECTROCHEMICAL MACHINING PARAMETERS - PYROMET X-15
25mm GUN DRILLING TESTS (FORWARD FLOW)

Test No.	Volts	Amps	Feed Rate (In/Min)	Pressure (Psi)	Electrolyte[a] Temperature (°F)	Flow Rate (Gpm)	Remarks
1	20	220	0.035	150	77	8+	Use 13-in.-long electrode, fiberglass/epoxy tape insulation, spacers on side of electrode. Tip diameter 0.904 in. Spacer diameter 0.965 in.
	24	250	0.040	150	84	8+ (at 2 in)	At 1' depth, increased rate to 0.040 inch/minute, volts to 24. At 2-1/2 in. depth, increased rate to 0.045 inch/minute.
	24	260	0.045	150	86	8+ (at 3 in.)	
	24	255	0.045	160	87	8+ (at 4 in.)	Removed electrode at 4.045 in. depth. Hole diameter 0.975 in. on inlet and 0.970 in. on bottom. Hole uneven on inlet and walls. Apparently due to turbulence of electrolyte caused by flow around spacers. Hole looked very good below spacers. Very good surface finish on wall of hole.
		Sparked out at 4.045 in. - could not restart.					

[a] 2-1/2-Lb/gallon $NaNO_3$

TABLE IXX. ELECTROCHEMICAL MACHINING PARAMETERS - 4340 STEEL 25mm GUN DRILLING TESTS (REVERSE FLOW)

Test No.	Volts	Amps	Feed Rate (In/Min)	Electrolyte* Press (Psi)	Electrolyte* Flow Rate (Gpm)	Temp (°F)	Hole Depth (In.)	Remarks
1	20	340	0.05	130	7.0	80	Start	Increased feed rate to 0.075 in. at 0.5-inch deep.
	20	520	0.075	155	6.4	85	1	
	20	520	0.075	160	6.4	88	2	Power supply shut down at 2.692-inches deep.
2	20	500	0.075	140	6.6	80	Start	Increased feed rate to 0.1 in/min at 0.5-inch deep
	20	635	0.10	155	6.0	85	1	
	20	640	0.10	155	6.0	88	2	Run Normal
	20	650	0.10	155	6.0	91	3	Electrolyte temperature control system not working during run.
	20	655	0.10	155	6.0	94	4	
	20	660	0.10	155	6.1	97	5	
	20	665	0.10	155	6.1	100	6	
	20	665	0.10	155	6.2	105	7	
3	20	500	0.075	140	6.6	80	Start	Demonstration run - stopped at 1-inch deep.
4	24	800	0.115	150	8.0	92	Start	Run Normal
	24	800	0.115	150	8.0	95	1	
	24	800	0.115	150	8.0	96	2	
	24	810	0.115	155	8.0	97	3	
	24	810	0.115	155	8.0	97	4	
	24	810	0.115	160	8.0	98	5	
	24	820	0.115	160	8.0	99	6	
	24	820	0.115	160	8.0	100	7	
5	22	780	0.115	150	7.0	83	Start	Run Normal
	22	780	0.115	150	7.0	84	1	
	22	780	0.115	150	7.0	85	2	
	22	780	0.115	155	7.0	86	3	
	22	780	0.115	160	6.9	87	4	
	22	780	0.115	160	6.9	89	5	
	22	780	0.115	160	6.9	90	6	
	22	800	0.115	165	6.8	91	7	

*4-lb/gallon sodium nitrate

TABLE IXX. ELECTROCHEMICAL MACHINING PARAMETERS - 4340 STEEL 25mm GUN DRILLING TESTS (REVERSE FLOW) (Concluded)

Test No.	Volts	Amps	Feed Rate (In/Min)	Electrolyte* Press (Psi)	Electrolyte* Flow Rate (Gpm)	Temp. °F	Hole Depth (In.)	Remarks
6	20	740	0.115	150	6.4	82	Start	Run Normal
	20	740	0.115	150	6.4	83	1	
	20	740	0.115	155	6.2	84	2	
	20	760	0.115	160	6.2	85	3	
	20	760	0.115	160	6.2	86	4	
	20	760	0.115	160	6.2	87	5	
	20	760	0.115	160	6.2	88	6	
	20	760	0.115	165	6.2	89	7	
7	20	750	0.115	150	6.4	82	Start	Run Normal
	20	750	0.115	150	6.2	82	1	
	20	760	0.115	155	6.2	83	2	
	20	760	0.115	155	6.2	84	3	
	20	760	0.115	160	6.2	85	4	
	20	760	0.115	160	6.1	86	5	
	20	775	0.115	160	6.1	88	6	
	20	775	0.115	165	6.1	89	7	
8	20	760	0.115	150	6.7	84	Start	Sparked out at 0.123-inch deep - Restarted
	20	760	0.115	150	6.7	85	1	Remainder of run normal
	20	760	0.115	155	6.6	86	2	
	20	775	0.115	160	6.5	87	3	
	20	775	0.115	160	6.4	88	4	
	20	780	0.115	165	6.4	89	5	
	20	780	0.115	165	6.3	90	6	
	20	780	0.115	170	6.2	91	7	

*4-lb/gallon sodium nitrate

For Test No. 4, feed rate was increased to 0.115 in/min and voltage was increased to 24 volts. For Test No. 5, the rate was maintained at 0.115 in/min and voltage decreased to 22 volts. Test No. 6, 7, and 8 were run at 0.115 in/min. feed rate and 20 volts. These tests allow a limited comparison of the effect of both voltage and feed rate on hole size. Figure 15 shows that hole size was decreased approximately 0.015-inch by increasing feed rate from 0.10 to 0.115 in/min. Figure 16 shows that hole size decreases as voltage is decreased. Both figures show the effect of increased hole size due to an increase in electrolyte temperature during the hole drilling operation.

The initial test to electrochemically gun drill Pyromet X-15 (Test No. 1, Table XX) was made in a short rod at 20 volts and a feed rate of 0.05 in/min. For Test No. 2, feed rate was increased to 0.08 in/min. At this rate, machining amperage was comparable to that obtained with 4340 steel at a feed rate of 0.10 in/min (Test No. 2, Table 1). (The higher amperage required to machine the Pyromet X-15, results from the difference in the chemical composition of the two materials). Test No. 3 was undertaken to drill a hole in a full length (8-inch) piece of Pyromet X-15. Power supply failure occurred three times during the drilling of this hole. As a result, oversize rings were produced in the part at the point of each machining interruption. With the exception of the rings, this part looked very good.

Pyromet X-15 part No. 4 was drilled to a depth of 8 inches without difficulty, producing a very good looking hole. Hole size increased about 0.008-inch due to the increase in electrolyte temperature.

Hole sizes for the 4340 and Pyromet X-15 parts are tabulated in Tables XXI and XXII, respectively. As mentioned previously, hole size for all parts increased in the direction of drilling due to the increase in electrolyte temperature during the machining of each hole. Proper control of electrolyte temperature would eliminate this problem.

In general, the diameter of the holes in both 4340 steel and Pyromet X-15 are round within 0.002-inch. Repeatability of size is within 0.001-inch for Test No. 6, 7, and 8 in 4340 steel, which were drilled at the same voltage and feed rate settings. Surface finish of the hole was approximately 50 rms for the 4340 and 16 rms for the Pyromet X-15, which is considered to be very good for electrochemically machined parts. Typical surface finish requirements for gun barrel bores are 32 rms. Although it was originally believed that a mechanical honing operation would be necessary after electrochemical drilling, these data indicate that such an operation may not be necessary for some materials. Flow lines and stray etching obtained with forward flow process were also eliminated by the use of the reverse flow tooling.

In summary, the reverse flow drilling process appears very promising for gun barrels, particularly for difficult-to-drill nickel and cobalt base superalloys. For these materials a significant economic advantage would be realized since they could be electrochemically drilled as cheaply as gun steel due to comparable material removal rates.

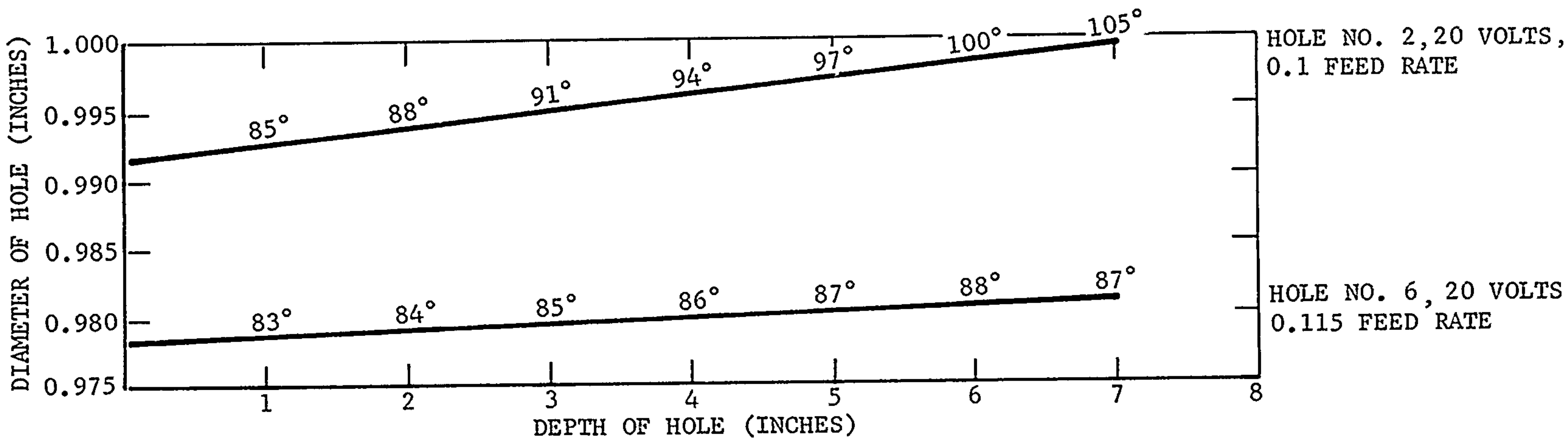


Figure 15. Effect of Feed Rate on Hole Size - 4340

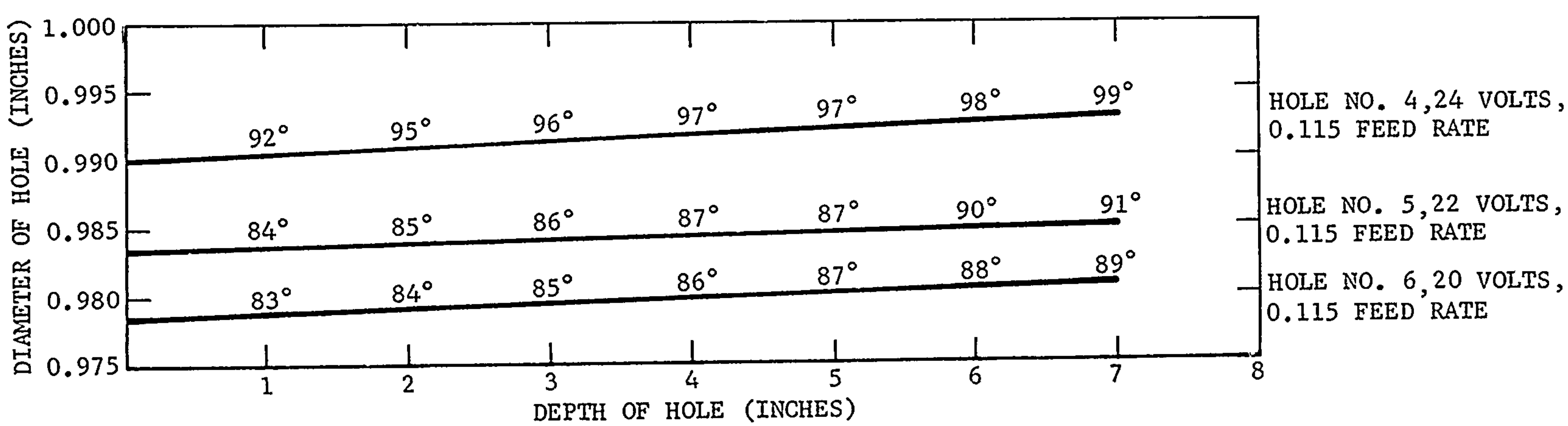


Figure 16. Effect of Voltage on Hole Size - 4340 Steel

TABLE XX. ELECTROCHEMICAL MACHINING PARAMETERS - PYROMET X-15
25mm GUN DRILLING TESTS

Test No.	Volts	Amps	Feed Rate (In/Min)	Press (Psi)	Electrolyte* Flow Rate (Gpm)	Temp (°F)	Hole Depth (In)	Remarks
1	20	440	0.05	150	5.4	80		Test run in short length rod-shutdown at 0.25 in. deep, pump failure.
2	20	675	0.08	150	3.5	80		Test run in short length rod at higher feed rate-shut down at 0.75 in. deep.
3	20	675	0.08	150	4.2	80	Start	Power supply shut down at 2.249 in. deep. Restarted after working on power supply.
	20	675	0.08	150	4.2	86	1	
	20	690	0.08	150	4.2	90	2	
	20	675	0.08	150	3.6	82	3	Power supply shut down at 4.776 in. deep. Restarted after working on power supply.
	20	675	0.08	155	3.8	86	4	
	20	675	0.08	150	3.6	82	5	
	20	675	0.08	150	3.7	87	6	Power supply shutdown at 6.350 in. deep. Restarted after working on power supply.
	20	675	0.08	150	3.6	83	7	
4	20	675	0.08	150	3.5	85	Start	Run Normal-Electrolyte temperature control system not working during run.
	20	675	0.08	150	3.5	87	1	
	20	700	0.08	150	3.8	92	2	
	20	700	0.08	150	4.0	95	3	
	20	700	0.08	155	4.2	100	4	
	20	710	0.08	155	4.2	102	5	
	20	710	0.08	160	4.3	105	6	
	20	720	0.08	160	4.3	107	7	
	20	720	0.08	160	4.3	108	8	

* 4-lb/gallon sodium nitrate

TABLE XXI - HOLE SIZE - 4340 STEEL DRILLING TESTS (REVERSE FLOW)

Barrel No.	2		4		5		6		7		8	
Diameter	A	B	A	B	A	B	A	B	A	B	A	B
Top			0.990	0.988	0.983	0.981	0.978	0.976	0.978	0.976	0.980	0.977
1"	0.992	0.990	0.990	0.988	0.983	0.981	0.979	0.976	0.979	0.977	0.980	0.977
2"	0.994	0.992	0.991	0.989	0.983	0.981	0.979	0.977	0.979	0.977	0.980	0.978
3"	0.995	0.993	0.992	0.990	0.984	0.982	0.980	0.977	0.979	0.978	0.980	0.978
4"	0.996	0.994	0.992	0.990	0.984	0.982	0.980	0.978	0.980	0.978	0.980	0.978
5"	0.998	0.996	0.992	0.991	0.985	0.983	0.980	0.978	0.980	0.978	0.98[illegible]	0.979
6"	0.999	0.997	0.993	0.991	0.985	0.983	0.981	0.979	0.981	0.979	0.981	0.979
7"	1.000	0.998	0.993	0.991	0.985	0.984	0.981	0.979	0.981	0.979	0.982	0.979
Bottom	1.000	0.998	0.993	0.991	0.985	0.984	0.981	0.979	0.981	0.979	0.982	0.979

TABLE XXII - HOLE SIZE - PYROMET X-15 DRILLING TESTS (REVERSE FLOW)

Barrel No.	3		4	
Diameter	A	B	A	B
Top	0.988	0.985	0.990	0.987
1"	0.988	0.986	0.991	0.988
2"	0.990	0.988	0.992	0.990
3"	0.986	0.983	0.994	0.991
4"	0.987	0.985	0.995	0.992
5"	0.986	0.984	0.996	0.993
6"	0.988	0.986	0.996	0.994
Bottom	0.989	0.987	0.997	0.994

SECTION V

PRODUCIBILITY STUDY

In order to predict production costs for electrochemical rifling of 25mm, 7-foot-long barrels, a cursory producibility study was conducted using Pyromet X-15 as a baseline material. Manhours were estimated for rifling quantities of 10, 100, or 1000 barrels per month for a period of one year. The estimates do no include cost of the electrochemical machining power supplies since this multipurpose equipment would necessarily be amortized over a longer period of time and for many other uses in addition to rifling. For comparison, estimates were prepared for conventional broaching utilizing previous data generated on 25mm Pyromet X-15 barrels. Similarly, the broaching estimates do not include cost of the rifling machine.

The estimates, summarized in Table XXIII show that the manhours required for electrochemical rifling are significantly lower than for broaching, particularly for large quantities. The tooling costs are also lower for electrochemical machining, since they can essentially be considered non-perishable, while the broaching cutters must be periodically sharpened and replaced. The electrochemical rifling tooling costs reflect costs of electrodes plus spares and associated plumbing and fixturing to machine one barrel at a time for all quantities considered.The higher tooling cost for 1000 barrels per month include added development required to fabricate high integrity 14 groove electrodes. The broaching tooling costs include cost of sine bar, cutter heads, and cutters with adequate spares to machine 10 and 100 barrels per month on a single machine. Quantities of 1000 barrels per month would require 8 rifling machines or development of wafer broaching techniques to rifle all 14 grooves simultaneously. Wafer broaching would be less time consuming than broaching only two grooves at a time, but anticipated tool life would be very low and necessary development costs are difficult to predict. Without this information, the tooling costs required for 8 machines were included in the estimates for the 1000 barrels per month, recognizing that this approach is not realistic for large quantities.

Based on the above, the cost advantages of electrochemical rifling are readily apparent. These cost advantages are magnified tremendously when difficult to machine alloys, such as nickel and cobalt base superalloys are considered as barrel or liner materials. The electrochemical rifling costs for these materials would not be unlike those for gun steel or Pyromet X-15 while conventional broaching costs would be prohibitive for some of the more difficult to machine alloys primarily due to the extremely low expected tool life. In addition, some of these alloys probably cannot be broached due to their poor machineability.

TABLE XXIII. COMPARATIVE COST ESTIMATES FOR PRODUCTION RIFLING

	10 Barrels/Mo		100 Barrels/Mo		1000 Barrels/Mo	
	Electrochemical	Broaching	Electrochemical	Broaching	Electrochemical	Broaching
Machining Time	1.0 *	4.0 *	1.0 *	4.0 *	0.4 *[a]	4.0 *
Set-up, equipment maintenance, and cleaning	2.2 *	1.0 *	1.5 *	0.1 *	0.6 *	0.1 *
TOTALS	3.2 *	5.0 *	2.5 *	4.1 *	1.0 *	4.1 *
			Tooling Costs Per Barrel			
No. Grooves Machined Simultaneously	7	2	7	2	14	2
Tooling Costs/barrel	$7.00	$45.00	$2.00	$19.00	$3.00	$18.00

*Man-hours

[a] Note machining time decrease is due to simultaneous machining of 14 grooves vs 7

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AFATL/DLDG	20		
AFATL/DLDA	1		
AFATL/DLDT			
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AFATL/DLDL	1		
AFML/MBP	1		
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13. ABSTRACT

A 17-month program was conducted to develop an electrochemical machining process for rifling 25mm, 7-foot-long gun barrels with gain twist rifling. Using a stationary electrode approach, a process and appropriate tooling and operating parameters were developed and demonstrated by rifling two barrels each of 4340 steel, Pyromet X-15 and CG-27, and one barrel each of Pyromet 860 and Alloy 718. Dimensional and metallographic evaluations of the rifled barrels verified that this process has high potential as a production rifling technique for steel and superalloy barrels. A producibility study was conducted to predict production costs. A secondary objective of the program was to investigate the feasibility of electrochemically drilling gun barrels in the 25mm size range utilizing a conventional forward flow and a new reverse flow process. The conventional forward flow process showed that deep holes could be drilled, but dimensional control could not be maintained. The reverse flow process showed considerably more promise with improved dimensional control.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Gain Twist Rifling						
Stationary Electrode Approach						
Pyromet X-15 Barrel						
Stationary Electrode						
4340 Steel Barrel						
Alloy 718 Barrel						
CG-27 Barrel						
High Performance Barrel						
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